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Fig. 22 — Lick Observatory

GREAT NEBULA IN ORION

The Problem of Volcanism

By
Joseph P. Iddings, Ph.B., Sc.D.

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THE SILLIMAN FOUNDATION

In the year 1883 a legacy of about eighty-five thousand dollars was left to the President and Fellows of Yale College in the city of New Haven, to be held in trust, as a gift from her children, in memory of their beloved and honored mother, Mrs. Hepsa Ely Silliman.

On this foundation Yale College was requested and directed to establish an annual course of lectures designed to illustrate the presence and providence, the wisdom and goodness of God, as manifested in the natural and moral world. These were to be designated as the Mrs. Hepsa Ely Silliman Memorial Lectures. It was the belief of the testator that any orderly presentation of the facts of nature or history contributed to the end of this foundation more effectively than any attempt to emphasize the elements of doctrine or of creed; and he therefore provided that lectures on dogmatic or polemical theology should be excluded from the scope of this foundation, and that the subjects should be selected rather from the domains of natural science and history, giving special prominence to astronomy, chemistry, geology, and anatomy.

It was further directed that each annual course should be made the basis of a volume to form part of a series constituting a memorial to Mrs. Silliman. The memorial fund came into the possession of the Corporation of Yale University in the year 1901; and the present volume constitutes the twelfth of the series of memorial lectures.

PREFACE

The following chapters on phases of the problem of volcanism were prepared for the course of Silliman Lectures at Yale University for the year 1914, and represent the lectures as they were then given, with slight elaboration in some parts. They were intended both for students of geology and for others who, while not having made a special study of the earth, are interested in its history and in theories respecting its origin and the possible causes of volcanic activity at or near its surface. For this reason the attempt was made to avoid, as far as possible, the use of somewhat technical terms; and when their use seemed unavoidable, they were generally defined, at the risk of making the treatment appear elementary. It seemed desirable also to reduce the problem to its simplest elements, and to attempt to trace each back to its fundamental basis, or to express it in terms of elemental principles. It is hoped that in this manner the discussion may appeal to a wider range of readers than would be interested in a more technical treatment of the subject.

The problem of volcanism involves many of the most fundamental questions in geology, and is necessarily modified by changes in our knowledge and conceptions of the physical characteristics of the earth as a whole, and of its relation to other members of the solar system and to other bodies in the universe, especially to the vast, indefinite nebulæ. Advancement in our knowledge of the physics and chemistry of igneous rocks and of their molten magmas, as well as in our information

as to their occurrence and distribution throughout known portions of the earth, must also modify our conceptions of volcanic operation, and must change from time to time the apparent relative importance of various factors that enter into the construction of the complex theory which may eventually serve to explain the manifold phenomena of volcanism. For this reason no formulation of a theory of volcanism can be anything more than an expression of current opinions on many unsolved problems in petrology, geology, and even in astronomy. The value of such an expression must rest upon the reasonableness of the arguments involved, according to our present state of knowledge of the factors concerned; it being understood that regarding unsolved problems there are often widely divergent opinions.

The author is under obligations to many friends for advice and suggestions during the preparation of the text, and for generous assistance in the matter of illustrations, especially to Professor Campbell of the Lick Observatory and Professor Frost of the Yerkes Observatory, to Dr. Hovey of the American Museum of Natural History, and to members of the United States Geological Survey and others whose names are mentioned in connection with the photographs which have been reproduced with their permission.

Joseph P. Iddings.

Washington, D. C., May 7, 1914.

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THE PROBLEM OF VOLCANISM

CHAPTER I

THE PHENOMENA OF VOLCANISM

A subject as old as the hills; a process that must have preceded them; a question that carries our thoughts back to a time when the earth may have been a nebula, "without form and void"; a speculation that has excited the liveliest imagination of men in all ages, and has taxed the intelligence of the ablest geologists; such is the problem of volcanism, which yet remains, as Dutton has said, first of the greater problems of physical geology.[1] "What is the potential cause of volcanic action," and how has it operated?

The invitation to bring to your attention this much discussed, and, to many of you, familiar problem was not extended, I take it, with any great expectations. The committee was well acquainted not only with the subject, but also with the author, and recognized the varied limitations of each. There was possibly a hope that the subject might be presented in the light of recent investigations in various fields, or that it might be reviewed from a standpoint somewhat different from that occupied by previous writers.

A glance at the various hypotheses that have been advanced in explanation of volcanic phenomena discovers the modifications that have been made in earlier ones in order to bring them into supposed conformity with facts subsequently established, or more in accord with some physical principle on which special emphasis is

[1] Dutton, E. C. Phil. Soc., Washington, Bull. 11, 1889, 51.

to be laid. Since there are many factors entering into the problem and its solution, there are many elements common to all attempted explanations, but they appear in very different proportions in different sketches of it, those closest to the observer often interfering with a clear view of the whole field. However, objects seen only from a distance are frequently misjudged or underestimated, and as close study is necessary for their perfect understanding, so the comprehension of a complex problem requires the thorough investigation of its several components and the proper adjustment of all its factors when each is finally known. The elements that enter into the problem of volcanism are so varied and some of them are so vast that no one student may hope to investigate them all himself, and it may be questioned whether any one may completely grasp the full significance of all the factors involved. A complete theory of volcanism must be the combination of contributions from workers in different fields of physical science, eventually coördinated to satisfy the various demands of the whole body of phenomena, material as well as kinetic.

The purpose of these chapters is to present the problem of volcanism, rather than a theory or a supposed explanation of it. Much remains to be learned of the elements that should constitute the solution, and before a satisfactory explanation can be reached the problem itself must be fully understood. Much that has been offered already by various geologists and writers on volcanism will contribute to the theory that will eventually be established, but many things have been suggested that appear to have been misapplied, or to have exaggerated the importance of some physical principle so as to make what may in some instances be

FIG. 1. MONT PELÉE, JULY 6, 1902

E. O. Hovey, Am. Mus. Nat. Hist.

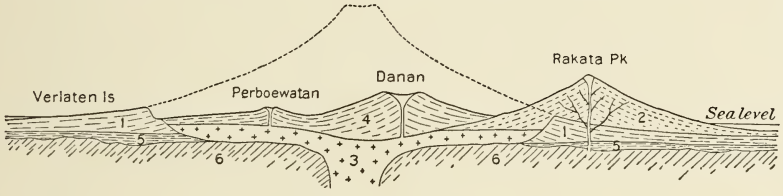

FIG. 2. PROFILE OF KRAKATAU BEFORE ERUPTION OF 1883

1. Older Hypersthene-Andesite. 2. Basalt. 3. Lava in Great Crater. 4. Younger Hypersthene-Andesite. 5. Quaternary and Recent Sediments. 6. Tertiary Terrane

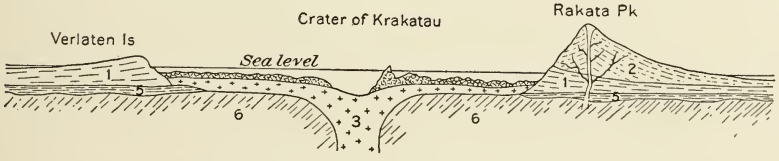

FIG. 3. PROFILE OF KRAKATAU AFTER ERUPTION OF 1883

R. D. M. Verbeek

a minor accessory operation appear in the rôle of a dominant or controlling action. Moreover, in some hypotheses the substance and material characteristics of the rocks themselves have been omitted, or known facts of geological dynamics have been overlooked. In presenting the problem of volcanism no attempt will be made to review systematically the hypotheses that have been proposed to account for volcanic action. Reference will be made to the most important in order to show how conceptions regarding the physics of the earth have advanced with growing knowledge of astronomy, physics, and chemistry.

It is proposed to call attention first to the phenomena of volcanism, in order to place clearly before you what it is that is to be explained and to show the wide range of phenomena that properly belong to volcanic activity; for in the minds of some geologists, in the past more than at present, there are special conceptions associated with the expression "volcanic," and others attached to the term "plutonic." The phenomena to which these terms have been applied are only slightly different manifestations of the same actions, the fundamental processes being the same.

Having noted the phenomena, it will be in order to point out the chief facts connected with their production that need explanation; then to present the facts that may be considered fairly well established which bear on the problem, and those views or hypotheses that may be reasonably associated with them, noting what still remains to be determined in some cases. The facts referred to relate to the physical character of the earth as understood with the present knowledge of astronomy, geology, and petrology, based on the foundations of physics and chemistry. In particular, the probable

dynamical status of the earth must be considered in order to account for the modes of occurrence of various bodies of intrusive rocks, and for the extravasation of molten magma from within outward, involving the consideration of its probable source, the cause of its eruption, as well as the process.

The Phenomena

While mild phases of volcanic activity become customary phenomena to the people of some regions and attract comparatively little attention, violent eruptions are always terrifying, and occasionally are appalling in their destruction of human life and property, as when in May, 1902, the eruption of Mont Pelée (Fig. 1), destroyed the city Saint-Pierre and its 28,000 inhabitants by a downward rushing blast of scorching acid vapor, with subsequent eruptions of similar scorching clouds (Fig. 4), besides vertical outbursts of vapors and showers of dust with floods of water in other parts of the mountain.[2] In August, 1883, the culmination of a series of increasingly violent explosions in the volcano of Krakatau threw back the inpouring sea and drove a wave of water high on the neighboring coasts of Java and Sumatra, engulfing more than 36,000 people with their villages and lands, sending a column of dust-laden vapor seventeen or twenty miles vertically. At its climax it projected dust into the upper regions of the atmosphere to a height that has been estimated at thirty miles, about 160,000 feet, producing atmospheric effects at sunset that were noticeable around the world for months afterwards. A block of rock that was thrown

[2] Lacroix, A. *La Montagne Pelée et ses Éruptions,* Paris, 1904.

FIG. 4. CLOUD OF HEATED GASES, MONT PELÉE, JAN. 25, 1903; HEIGHT, 2300 METERS

A. Lacroix

thirty miles is estimated to have risen thirty-one miles in its flight.[3]

The island, on which two small craters, Danan and Perboewatan, renewed their activity in May of that year, was blown up during the final eruptions, and in its stead a circular pit 1,000 feet deep marks the submerged crater of the latest eruption (Figs. 2 and 3). The volcanic cone of Rakata was cut in two and the structure of the remaining half was exposed in a vertical escarpment (Fig. 5).

In violent eruptions of this sort the upward rushing currents of gas and dust are sometimes overcharged with electricity that darts forth in flashes of lightning and exploding stars of blinding brilliancy, accompanied by the roar of detonations like that of a continuous cannonade, so graphically described by Kennan at the eruption of Mont Pelée in the night of May 26, 1902 (Fig. 6), when "stars of volcanic lightning were flashing out constantly in every part of the vapor column two miles high, bursting not only in the black canopy overhead, but far eastward over the ocean seven miles from the crater."[4] Similar electrical phenomena accompanied the eruption of Tarawera, New Zealand, in June, 1886, and also were witnessed from shipboard during the great eruption of Krakatau, when at a distance of fifty miles a ship was covered with phosphorescent mud.

A hundred years earlier, in 1783, a remarkable series of eruptions occurred in Iceland, beginning in May with a submarine eruption southwest of Reykjanes, that formed a temporary volcanic island from whose crater

[3] Verbeek, R. D. M. *Krakatau,* Batavia, 1885-1886, and *Report of the Krakatoa Committee of the Royal Society,* London, 1888.

[4] Kennan, George. *The Tragedy of Pelée,* New York, 1902.

pumice flowed over the sea for more than a hundred miles.[5] In June violent earthquakes near Skaptar Jökull were followed by immense outpourings of lava from twenty-two orifices along a line over ten miles in length, the so-called Laki fissure. Streams of lava flowed across the country, filling river beds, deep gorges, and broad valleys, extending for distances of twenty-eight and fifty miles, a volume estimated as more than that of Mont Blanc. Pumice and dust were thrown over the greater part of Iceland, and some fell beyond the Faroe Islands. Eruptive activity continued for three months and even into January, 1784. In April of this year eruptions took place near Skeidhardjökull, in a range of snow-covered mountains, producing terrible floods, or Jökellöb, of water, ice, sand, and volcanic dust, which further devastated the land. Indirectly, through hunger and disease, these eruptions caused the death of over one-fifth the population of the island, and of 230,000 head of live stock.

From catastrophes like these one obtains the impression of gigantic forces, which in the eruption of Tomboro on Sumbawa, in 1815, scattered dust over an area of nearly 1,000,000 square miles, an amount of material estimated by Zollinger at fifty cubic miles, and by Junghuhn to be equal to 185 mountains the size of Vesuvius.[6]

In contrast to these paroxysmal explosions are the wells of liquid lava boiling tranquilly and continually from one year's end to the other, through decades and centuries in some instances, as in the lake Halemaumau

[5] Thoroddsen, Th., trans. by G. H. Boehmer. Smithsonian Institution, Report, 1885, part 1, 495.

[6] Junghuhn, F. *Java*, 1857. See also Geikie, A., *Textbook of Geology*, 4th Ed., 1903, vol. 1, 294.

FIG. 5. ESCARPMENT OF KRAKATAU AFTER ERUPTION OF 1883

R. D. M. Verbeek

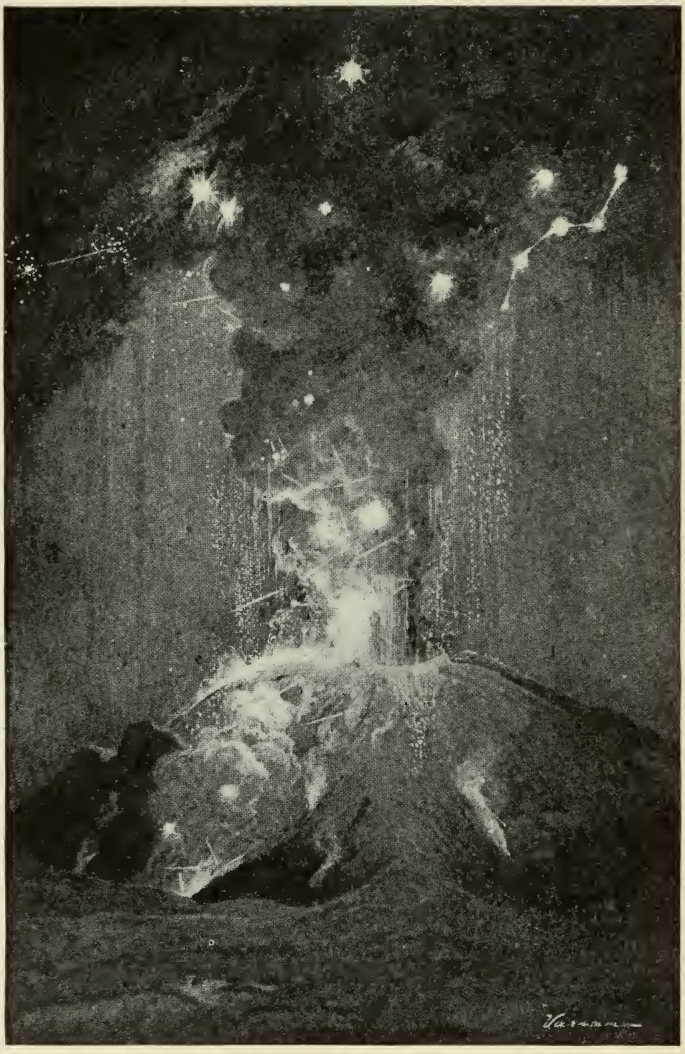

Fig. 6. Mont Pelée, May 26, 1902

Geo. Varian

in the great crater of Kilauea (Fig. 7), or in the small crater on the summit of Stromboli; ejecting no dust, almost no lumps of scoria, with no streams of lava overflowing the crater's rim, but at Kilauea occasionally breaking through the volcano's side. In most active volcanoes the conduit beneath the crater contains molten lava covered with slag, or dust, and broken rock, except when it boils with escaping gases that lift the crust and reveal the glowing lava underneath. The molten liquid in such cases stands in the conduit extending to unknown depths like water in a well, its surface sinking at times, rising at others. In some cases it boils rhythmically, at regular intervals emitting great bubbles of gas, after which it collapses with a thud like that of a boiling geyser pool, such as the Excelsior in the Yellowstone National Park. At times a greater rush of gases carries up the fiery liquid, lifting the upper portion that weighed the lower down, releasing more gases, which in turn lift their surrounding load, until the outward rushing flood of quick-expanding lava-foam spouts upward like some giant geyser column of exploding froth. From these roll clouds of vapor charged with pumice dust, the so-called "smoke," which, according to the movement of the air, if this be still, rise as a column to spread at top like an Italian pine, or drift off lazily in a summer's trade, or in a gale of wind stream swiftly leeward.

The clouds of vapor that rise from craters and lava streams are mostly water vapor, judging by the precipitation, direct tests in a few cases, and by chemical study of igneous rocks and lavas themselves. Other gases are abundant in some instances, but from the nature of eruptions little has been learned, or ever will be discovered, from direct observation and investigation of violently active craters where gases emerge in greatest

volumes. For the conditions are such as Milton has described, when "the shattered side of thundering Etna whose combustible and fuelled entrails thence conceiving fire, sublimed with mineral fury, aid the winds and leave a singed bottom all involved with stench and smoke."

Not only the danger of exploding molten lava and ruptured slag, but scalding vapors, acid fumes, and scorching heat preclude close approach and the collection of gases. Anything like a quantitative determination of the gases emitted by such volcanic eruptions is out of the question, and we must be content with vague speculation which will differ according to the information and judgment of the speculator. Moreover, it is to be expected that different eruptions will vary greatly, not only in the volume of gases emitted but in the relative quantities of the various kinds. This is plainly indicated by the volumes of clouds given off from lavas in various craters, as well as from the same volcano at different periods of activity; and also by the condition of the lava at the time of eruption, or after it has solidified.

It must be remembered, however, that in volcanic phenomena, as in all others, appearances may be deceptive, for clouds may be caused by gases or vapors of water, sulphurous oxide, carbonic oxide, hydrogen chloride, or by mixtures of these compounds, and others; and some of the aqueous vapor may be derived from the atmosphere involved in the uprising current which is at first heated, but later is cooled at higher altitudes.

On the other hand, water gas may escape in large volumes without becoming visible as clouds of any kind. In the crater of Taal on Luzon in the Philippines, in 1910, where ponds and boiling pools were steaming vigorously in the moisture-laden air of the tropical lake that surrounds the volcano, a column of hot gas was

rushing from a hole, six or eight inches in diameter, in dry rock in the midst of the crater. It escaped under such pressure that it roared loudly, and blew out anything thrown into it. No cloud or trace of vapor was visible above it, and it would be properly described as dry gas, yet when collected in a tube it was found to be largely water gas which condensed into abundant water, that fell in a stream of drops in a collecting flask. Its temperature at the orifice was over 400° C., that is, above the critical temperature of water. It was water gas, not vapor, and as such was dissipated into the atmosphere without condensation.

From the lava pool of Kilauea, whose surface temperature is about 1000° C., water gas should issue much above its critical point, and pass into the tropical air, however moist, without producing clouds. Recent observations by Day and Shepherd on the gases from the lava of Kilauea have demonstrated the escape of water gas in abundance, accompanied by that of nitrogen, carbon dioxide, carbon monoxide, sulphur dioxide, free hydrogen, free sulphur, and insignificant quantities of chlorine, fluorine, and perhaps ammonia.[7]

In most instances the gases that have been collected in volcanic districts are from fumaroles or solfatara immediately over once active craters, or on the flanks, or at the base of volcanic cones. In some cases the gases are wholly magmatic, escaping from the cooling lavas, excluded during the process of crystallization and contraction. In some instances they may have been driven from surrounding rocks, especially sedimentary carbonates, by heating and chemical replacement during metamorphism by the adjacent intruded lavas. The

[7] Day, A. L., and Shepherd, E. S. Bull. Geol. Soc. Am., 24, 1913, 573.

chief gases that have been noted in this way are water vapor, hydrogen, nitrogen, oxygen, carbon dioxide, carbon monoxide, hydrogen sulphide, sulphur dioxide, hydrogen chloride, chlorine, methane or marsh gas, hydrogen fluoride, and silicon fluoride. Argon has been collected from a fumarole on Guadeloupe, at Santorini and from Mont Pelée.[8] Sainte-Claire Deville found that hydrochloric acid, chlorine, and fluorine escape from the hottest fumaroles, that at less active vents sulphur dioxide is most abundant, and that from the cooler ones hydrogen sulphide, carbon dioxide, and nitrogen are given off; carbon dioxide and nitrogen escaping from all fumaroles which he investigated.[9] Fouqué found hydrogen more abundant in the hotter fumaroles at Santorini, and from a lava beneath the sea at this place obtained gas that was 56.70 hydrogen, 21.11 oxygen, and 21.90 nitrogen.[10]

The gases inclosed in volcanic rocks, which have been studied in the laboratory, are those that did not escape at the time of eruption, or of intrusion into fissures in other rocks, or which subsequently evaporated from their mass, or escaped through pores and cracks. Gases that have been determined directly as included or occluded in igneous rocks are combinations of oxygen, hydrogen, carbon, and also nitrogen; such as CO_2, CO, H_2, CH_4, and N_2. The method of extraction by heating rock powder must yield gases which in large part result from decomposition of solid compounds, and from chemical interaction under the influence of heat, as remarked by R. T. Chamberlin, so that the results of

[8] Moissan, H. *Comptes Rendus,* 138, 1904, 936. Lacroix, A. *La Montagne Pelée et ses Éruptions,* Paris, 1904, 187.

[9] Deville, Sainte-Claire. Ann. de Chim. et Phys., 52, 1858, 60.

[10] Fouqué, F. *Santorin et ses Éruptions,* Paris, 230.

FIG. 7. LAVA POOL IN KILAUEA, HAWAII, MAY 23, 1912

A. L. Day

these investigations must be treated very cautiously.[11] They represent one of the ways in which gases may be driven from solid rocks by the heat of intruded lavas, as already mentioned. Gases imprisoned in igneous rocks appear as microscopic bubbles within cavities in a few minerals, usually in quartz, but have seldom been specially analyzed. Inclusions of water are common in quartzes of granites and other quartzose igneous rocks, and inclusions of liquid carbon dioxide are much less common, the most abundant known being found in quartz in the pegmatite of Branchville, Connecticut, from which A. A. Wright obtained water, carbon dioxide, small portions of nitrogen, and traces of H_2S, SO_2, H_3N, F, and possibly Cl.[12]

Of the elements that escape as gas some parts remain fixed in mineral compounds in the crystallized lavas. By far the most abundant is water or hydroxyl, which is an essential component of mica and hornblende, and in some rocks is fixed in primary analcite. It is a prominent constituent of some rock glasses, forming several per cent. Carbon dioxide or other carbon compounds are rarely essential constituents of primary minerals in igneous rocks, occasionally appearing as in pyrogenetic cancrinite. They are entirely absent from many rocks analyzed. Chlorine, fluorine, and sulphur occur in such primary minerals as apatite, the sodalites, some micas, amphiboles, pyrite, and other sulphides. Compared with water in the average of the rocks analyzed each is about one-fifteenth as much by weight, or water may be said to be five times as abundant as all of them together.[13]

[11] Chamberlin, R. T. "The Gases in Rocks," Carnegie Institution of Washington, 1908, 61.

[12] Am. Jour. Sci., 21, 1881, 203.

[13] Clarke, F. W. Bull. 419, U. S. Geol. Survey, 1910, 6.

The potency of acid fumes to decompose rocks and make new compounds, many of them soluble in water and easily removed, is shown by the sublimates and efflorescent deposits within volcanic craters, or about solfatara. This is well illustrated by the crater of the volcano Taal, in the Philippines, visited in January, 1910. The cone rises from the middle of a great lake, Laguna de Bombon, almost at sea level. From a distance it appears as a dark, low mountain from which rise clouds of vapor (Fig. 8). It was known to consist of dark gray, almost black, basaltic andesite.

Approaching it by boat from the east shore of the lake in the early morning, as the full moon settled behind a great bank of clouds and the dawn began to show itself, the slopes of the volcano took on pale tints of gray and yellowish green as the encrusted ashes, or tuffs, of the spurs, with their thin mantle of sparse grass, caught the growing light. Here and there in ravines clusters of luxuriant shrubs or trees added patches of deep, rich green. My expectation of a dark basaltic cinder cone changed to a vision of delicately tinted light, that might have been the dream of some joyous artist. Landing on a narrow beach of shells, the boat was hauled up to rest, while George Adams and I ascended the barren flanks of the outer cone to the rim, 600 feet above the lake.

Here another surprise awaited us, for instead of black, dark gray, or chocolate-colored rocks, the rising sun lit up pale gray cliffs tinted with pink, yellow and light brown, the precipitous walls of the great deep pit, in places rising a thousand feet above its floor of sand, old lava, and a milky lake, with clusters of low cones and minor craters (Fig. 9).

Great clouds of vapor rose from small lakes and muddy pools, or rushed from open holes, roaring and

FIG. 8. VOLCANO TAAL, LAGUNA DE BOMBON, LUZON

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filling the air with acid fumes, deadly to breathe (Fig. 10). But the old crater is large and the monsoon breeze was strong, so we were able to wander about for hours studying the lesser craters and collecting rocks that are dark enough when broken open, their surface only bleached by the acids that have produced encrusting compounds and salts colored with four-fifths of the spectrum. The surface of one great mound, from the base of which rushed a stream of white and reddish-brown vapors, was coated as with velvet in shades and tones of yellow, grading into brilliant greens. A neighboring cone of dark brown tuff was whitened over as by a thick hoar frost. Near by, a lake of greenish water steamed in clouds that shrouded a high pyramid of rock within, and veiled with blue mist the distant cliffs. Along the shallow, muddy margin of the lake were pools of grass-green, emerald or turquois water draining through pale lavender-tinted mud. The low banks above the water were streaked with brilliant reds, yellows, grays, and browns. For intensity of coloring and variation in tones the crater of Taal, at this time, surpassed the beauty of the hot springs of the Yellowstone National Park.

But the beauties of Taal are evanescent; heavy tropical rains wash off the soluble salts, leach out the delicate tints, and dull the brilliant colors, leaving somber lavas and opalescent pools, as we found them after a heavy shower on our second visit two months later. The swollen lake was pouring a stream of water into the large steam vent already mentioned, that roared and spluttered in remonstrance. Ten months later, in January, 1911, the volcano blew up gas and tuff that covered the mountain, and rushing down its western slope destroyed the people on it and those upon the west

shore of the lake, killing at least 1,300 persons with poisonous gases and scalding mud,[14] and leaving a crater that has become flooded with water from the surrounding lake (Fig. 11).

The commoner sublimates that are deposited from volcanic vapors are chlorides of sodium, ammonium, iron, and other elements, sulphates and sulphur, sometimes in large quantities, as in the crater of 1893 on Azuma-Yama, or Nasu-Yama, in Japan, where steam and sulphur emerge from many vents from which much sulphur is being collected. Boric acid occurs in the crater of Vulcano, one of the Æolian Islands. Arsenic, antimony, tellurium, cobalt, zinc, and bismuth have been found in small quantities in some places. Silicates like those forming mineral constituents of the crystallized lavas occur, lining cavities in such a manner as to demonstrate that they have been deposited from vapors carrying them in solution, that is, in the form of silicate vapors, but their quantity is exceedingly small.

The former presence of abundant gases in molten lavas is shown by the inflation of the cooled rock, such as pumice and vesicular slags, and by the form of the particles of tuff which are fragments of exploded pumiceous lava. In these cases, however, no quantitative estimate can be made of the amount of gas originally held in solution, for the more liquid lavas permit the escape of gas with less vesiculation than more viscous lavas, and the viscosity is in part a function of temperature, which may be different for lavas erupted from different conduits, or at different times from one and the same conduit; and it is also a function of the chemical composition of the lava, basaltic lavas being much more liquid than rhyolitic ones at the same temperature.

[14] Pratt, W. E. Philippine Jour. Sci., 6, 1911, 63.

FIG. 9. CRATER OF TAAL, BEFORE ERUPTION OF 1911

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FIG. 10. CRATER OF TAAL, BEFORE ERUPTION OF 1911

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Moreover, the weight upon any portion of a mass of lava controls the possible escape and expansion of the dissolved gas and the apparent vesiculation of the cooled rock.

All is not volcanic that is ejected from a crater or accompanies a volcanic eruption. As already said, gases may be driven out from surrounding rocks by heating and by chemical reactions. Floods of water sometimes proceed from crater lakes, and fish have been erupted in this way from Volcan d'Agua in Guatemala, in 1540; from Imbaburu, near Quito, in 1691, and elsewhere. Floods result from melting snow and ice upon the renewal of activity of snow-clad volcanoes, and blocks of ice with frozen mud and stones were ejected from a crater in the Askja Valley in Iceland in 1875. Abundant fragments of sedimentary and metamorphic rocks often characterize the earlier eruptions of a volcano in a new locality, the fragments coming from the surface rocks and the channel ruptured by the outburst.

An interesting example of miniature eruptive activity is furnished by hot springs and geysers in volcanic regions, such as the Yellowstone National Park, Iceland, and northern New Zealand. The material erupted is non-volcanic, being underground drainage water whose supply is noticeably dependent on seasonal precipitation in some instances. The energy, however, is volcanic heat derived from fissures or other orifices associated with active or decadent volcanism. The analogy between the eruptions of geysers and volcanoes is striking and significant, and will be discussed later on.

As to the lavas themselves much is to be said, more than can be included in a part of one chapter. They are the substances that flow from the depths of the earth,

that arrive at its surface glowing like molten iron from a furnace. They are liquids having high temperatures. Some have been determined to be 1000° C. at their contact with the atmosphere in craters, some have been seen to issue from orifices at white heat, about 1500° C. How much hotter they may be at considerable distances below the surface of the earth, before entering the cooling zone, there is no direct means of knowing. They are many liquids, not one substance like water. Volcanic lavas are not one compound with uniform characters, but liquids having different compositions and different physical properties, quantitatively. These have been discovered partly from a study of the solidified lavas, as rocks, investigated in the laboratory to determine their chemical and mineral compositions; or melted in crucibles to study the properties of their liquid phases; partly from a study of the flowing lavas at the time of eruption to observe their behavior as viscous fluids, or of the solidified masses to learn from their shapes and dimensions the probable condition of the lavas just before they solidified.

Of the lavas known to have reached the earth's surface and to have poured out upon it, the greater number have intermediate compositions between certain extremes, the whole number forming graduated series of mixtures of liquid compounds, chiefly silicates, which, when crystallized, are common rock-minerals; usually feldspars, with quartz in some instances, or pyroxenes, amphiboles, micas, olivine, magnetite, or nephelite, leucite, and others.

The commoner lavas are called andesites of various kinds, and consist chiefly of lime-soda-feldspars, with pyroxene, hornblende, or mica, and small amounts of

FIG. 11. CRATER OF TAAL, AFTER ERUPTION OF 1911

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Fig. 12. Parry Island Volcano, Bogosloff Group, Aleutian Islands, 1906

orthoclase molecules and free silica, which may be tridymite or quartz when properly crystallized. At one extreme of the lava series are rhyolites, with more alkalic feldspars than the andesites contain, and much quartz. When completely crystallized they may consist chiefly of orthoclase and albite feldspars, with quartz, but when uncrystallized are rock glasses, obsidians. At another extreme of the lava series are basalts of many kinds, some of which consist of distinctly calcic feldspars, pyroxene, olivine, and magnetite. In one known instance, which is very exceptional, however, a lava rock contains over 50 per cent of magnetite, and about 25 per cent each of labradorite and augite. Other lavas of extreme composition are rich in nephelite and leucite; others almost wholly augite.

It is to be expected that such different mixtures, when molten liquids, will possess different viscosities at the point of saturation or crystallization, and at any one temperature, and also different densities. This has been found to be true so far as investigation has gone in this direction, but much remains to be learned. Ordinary basalt, such as the "trap" of West Rock, New Haven, when melted before an oxyhydrogen flame is very liquid, and drops from a rock fragment almost like water from melting ice, whereas rhyolitic obsidian near its melting point is extremely viscous, almost as stiff as the solid glass. Moreover, the melting point of the rhyolitic lava is much higher than that of basalt, probably 50 per cent higher. The presence of gases in lavas reduces their viscosity considerably, as may be seen upon melting obsidian containing 0.5 per cent of water, and melting the same glass after the water gas has been driven off. The former is much more liquid at the melting tempera-

ture, which is also lower than that of the less gaseous glass.

Observed in a molten condition in craters, issuing from fissures on the flanks of volcanic cones, and flowing as streams down their slopes or along drainage channels, lavas appear to possess very different degrees of viscosity as well as very different temperatures. In the crater of Kilauea, Hawaii, the floor of which is a movable stage of solid lava, known to rise and sink several hundred feet, there is a lake of basaltic lava varying in size at different times. From its boiling surface fountains of molten liquid often spout thirty or forty feet vertically. Usually it is quiet, as though most of the surface were covered by a thick scum, which at times cracks apart and permits the red-hot lava beneath to appear. At the time of his second visit, in 1887, James D. Dana noted that in the space kept open by boiling lava "the splashing at the margin due to the escape of vapor bubbles had all the freedom of movement of splashing waves on a sea coast."[15] But this does not indicate that the lava possessed the same liquidity as sea water, for its mass is three times as great, and its momentum proportionately large.

Many interesting observations have been made on eruptions of basaltic lava from Mauna Loa, whose crater is about 10,000 feet higher than that of Kilauea and about twenty miles distant horizontally. In August, 1872, the crater of Mauna Loa was violently active, fountains of lava spouted from it to heights of 200 and 600 feet; the altitude of the bottom of the crater being about 12,800 feet. The crater of Kilauea was unusually active at this time, but no earthquakes occurred in either

[15] Dana, J. D. *Characteristics of Volcanoes,* New York, 1890, 114.

Fig. 13. Fossil trees, Yellowstone National Park

J. P. Iddings, U. S. Geol. Surv.

locality.[16] In 1852 lava burst from the side of Mauna Loa about 2,800 feet below the level of the crater floor. At first it rose in a fountain 400 and 500 feet in height, at times as high as 700, from a lava basin 1,000 feet in diameter. The width of the fountain at its base was from 100 to 300 feet, rarely 400 feet. At times it shot up into a tapering spire of 700 feet, then rose in a grand mass 300 feet broad with jets at the top like pinnacles of gothic architecture.[17] At the base of the fountain the lava was white-hot, higher up it became red, then grayish red and gray. The stream from it flowed for twenty miles and in places was 200 and 300 feet deep. The eruption continued for twenty days, and the neighboring country was covered with a kind of pumice for a distance of ten miles. No earthquakes preceded this eruption, and Kilauea was quiet.[18]

At the time of the great eruption of 1859, lava burst from the side of Mauna Loa at an altitude of about 10,500 feet, and gushed in fountains 300 and 400 feet high, and white-hot at base. It dashed down the slopes in cataracts and rapids at such a rate that "the eye could scarcely follow it." The lava of 1843 flowed through tunnels of its outer shell with such speed that large stones thrown on it were carried away instantly out of sight before sinking into the stream. The lava of 1859 flowed for ten miles with a motion more graceful than that of water. The lava of 1855 traveled in places at an estimated speed of forty miles an hour, but the front of the stream moved at a rate of one mile a week. The lava of 1859 traveled thirty-three miles in eight

[16] Coan, T. Am. Jour. Sci., 4, 1872, 331, 407, 408.
[17] Fuller. Am. Jour. Sci., 14, 1852, 258.
[18] Coan, T. Am. Jour. Sci., 14, 1852, 105, 219; 15, 1853, 63.

days. At the front of the stream no molten lava was visible, the only appreciable motion being the rolling of jagged fragments of solid lava of all sizes down the front of the embankment. At times, however, the molten fluid broke through its crust. When it reached the sea the liquid lava was still red hot, having flowed under cover of its own crust for at least twenty-five miles.

According to W. L. Green it flowed into the sea over a low shelf about ten feet above water and 500 or 600 feet wide, coming from under the crust in great red hot, flattened, spheroidal masses, ten or fifteen feet wide and four to six feet deep. No steam, vapor, or gas was to be seen coming from the lava until it had disappeared under water, when a puff of steam rose to the surface.[19] This vivid description explains the production of aggregated masses of spheroidal basalt, such as form the Cyclopean rocks off the coast of Sicily near Acireale at the foot of Etna, and elsewhere, which are sometimes called "pillow" lavas.

In contrast to these fluid gushings of highly liquid lavas are the slow extrusions of stiff, viscous masses, such as the andesitic lava of the Isles of May at Santorini,[20] which rose from the sea like an island of solid rock in 1866, or like the dacitic lava of Ilopango[21] that appeared above the waters of the lake in Salvador in January, 1880. These more siliceous and more viscous lavas were still further stiffened by the cooling water into which they slowly flowed. This is largely the nature of volcanic eruptions in the Aleutian Islands, where, with Robert Browning, we may imagine:

[19] Green, W. L. *Vestiges of the Molten Globe,* 1887, 163, 270, 280.
[20] Fouqué, F. *Santorin et ses Éruptions,* Paris, 71.
[21] Russell, I. C. *Volcanoes of North America,* New York, 1897, 147.

Fig. 14. Fossil tree trunk, Yellowstone National Park

J. P. Iddings, U. S. Geol. Surv.

The wroth sea's waves are edged
With foam, white as the bitten lip of hate,
When in the solitary waste, strange groups
Of young volcanoes come up, cyclops-like,
Staring together with their eyes on flame.

One of these young volcanoes, Parry Island, in the Bogosloff group, is shown in Figure 12. It was erupted in 1906.

From modern and historic instances we judge of past occurrences. As the dust of Vesuvius buried the houses and temples of Pompeii, one great explosion overtaking belated people, and with them entombing relics of their graceful art, so the tuffs and breccias of more ancient volcanoes in Eocene times have ruined forests upon their slopes, burying leaves and trunks, whose great size shows the years or centuries that elapsed between the gigantic outbursts, that time after time destroyed successive growths of trees, until the accumulated strata grew to heights of 3,000 and 4,000 feet, as at Fossil Forest in the Yellowstone National Park, and in the Müller Mountains in Central Borneo[22] (Figs. 13 and 14).

Great accumulations of stratified tuffs and breccias have required thousands of years to form, during which period volcanic cones may have become obliterated by repeated explosions and dissecting rains. Chains of volcanoes produce ranges of breccia and lava flows, as in the Andes of South America, the San Juan Mountains in Colorado (Fig. 15), and elsewhere. Widespread showers of tuff and rock fragments form plateaux of breccia. Floods of liquid lava like that from the Laki fissure in Iceland, filling surface channels and depres-

[22] Molengraaff, G. A. F. *Geological Exploration in Central Borneo*, Leyden, 1902.

sions, cover vast tracts of level country, forming lava plains, like those of Idaho and the Deccan traps of Western India.[23] Not one outburst, but repeated flows through long ages have built the plateaux of the Deccan, the extensive lavas of the Columbia River, and the piled-up layers of the Cascade Range.

In some instances enormous volumes of lava have poured out at one eruption, judging from the size of the continuous rock masses formed, such as the rhyolite masses of the Yellowstone Park plateaux. Exposures 1,000 and 2,000 feet high show continuous bodies of rock of these thicknesses extending for miles.[24] However, there is probably more than one such great body of rhyolitic lava in this region, erupted within one period of volcanic activity. Similar extensive outflows of rhyolite or quartz-porphyry occur in Colorado, Mexico, and in Argentina.

Lavas that burst from the sides of volcanic cones flow through more or less vertical fissures in which the lava when solidified becomes dikes of andesite, basalt, or other rocks (Fig. 16). Fissures may occur on any side of a cone, and eventually a radiating system of dikes may surround the conduit that feeds the crater. Such dikes appear in Monte Somma, the outer wall of ancient Vesuvius. They may be more numerous on the weaker side of a cone, and not equally distributed around it, as in the dissected volcano of Crandall Basin in the Yellowstone National Park.[25]

When the material of a cone is somewhat stratified,

[23] Oldham, R. D. *Manual of the Geology of India,* Calcutta, 2d Ed., 1893.

[24] Hague, A., Iddings, J. P., *et alii.* U. S. Geol. Survey, Mon. 32, part 2, 1899, 375.

[25] Iddings, J. P. U. S. Geol. Survey, Mon. 32, part 2, 1899, 215.

Fig. 15. Volcanic breccia, North Lookout Peak, Colo.

W. Cross, U. S. Geol. Surv.

FIG. 16. DIKES CUTTING VOLCANIC TUFFS, MIDDLE FORK OF CIMARRON CREEK, COLO.

E. Howe, U. S. Geol. Surv.

with beds of tuff and lava flows, the rupturing fissures may in places follow planes of separation between the strata, and the intruded lava solidify in sills, as on the Isle of Skye, in the San Juan Mountains in Colorado (Fig. 17), and elsewhere.[26] Sills and dikes often occur intersecting one another. An excellent example of the intersection of dikes and sills cutting lava flows and tuffs is furnished by the escarpment of Krakatau shown in the photograph taken shortly after the explosion of 1883 (Fig. 5).

When the lava in the conduit of a volcano solidifies, the resulting body of rock is pipe-like or much more irregularly shaped, and is called a stock or neck. Exposed to view by erosion, or faulting, it is seen to pass outward in places into dikes, less often into sills, and to be traversed to a greater or less extent by smaller bodies of solidified lava, the last eruptions through the choking conduit. According to the extent to which erosion has cut down the volcanic cone, the stock may be exposed, surrounded by volcanic tuffs and breccias, above the underlying rocks that formed the earlier surface of the earth, which may have been sedimentary formations, as is the case of the denuded volcano of Crandall Basin. Faulting may have displaced the volcanic cone, and erosion exposed the core and associated dikes within the sedimentary strata that underlaid the cone, as at Electric Peak in the Yellowstone National Park.[27] Erosion may have cut diagonally through a cone, leaving on one side a mountain of breccia adjacent to the core, or stock, while the more deeply eroded portion reveals metamorphic schists

[26] Harker, A., and Clough, C. T. Mem. Geol. Survey, Great Britain. *Tertiary Igneous Rocks of Skye,* 1904, 236, 272, and 292.

[27] U. S. Geol. Survey, Mon. 32, part 2, 1899, 89.

overlaid by a wedge-shaped covering of Cambrian sediment cut by the solid lava that plugged up the volcanic conduit. This is the case of the dissected volcano of Haystack Mountain in Montana,[28] while to the north of it, in the Crazy Mountains, Montana, erosion has revealed a great stock surrounded by innumerable sills and dikes traversing Tertiary sandstones and shales, with no remnant of extrusive lavas, tuffs or breccias.

The rocks of these exposed stocks, dikes, and sills are similar in their variations in crystallization and texture. Some were parts of volcanic cones, and as such are as truly "volcanic" as the tuffs and lavas that reached the atmosphere before solidifying. Some are aphanitic porphyries and may be called andesites, basalts, and other kinds of surface lavas. Some are as coarsely crystallized as ordinary granites and diorites, and, in fact, are such rocks, in these cases clearly volcanic; parts of volcanoes above their base of sedimentary rocks. The same kinds of rocks occur intruded in non-volcanic formations beneath volcanic cones, lavas that solidified within fissures having various shapes and positions. In some regions erosion has been so extensive that it is not possible to determine whether extrusive lavas ever overlaid the former surface of the earth in these places, and whether the intrusive rocks were connected with volcanic cones. However, all extruded lavas do not build up cones, and a conical mountain is only one manifestation of eruptive activity, resulting from the continuous or repeated emission of molten material from a restricted orifice, about which it becomes piled up, as in the graceful volcano, Mayon, on Luzon, in the Philippine Islands (Fig. 18).

[28] U. S. Geol. Survey, Atlas Folio, 1. J. P. Iddings and W. H. Weed; also W. H. Emmons, Jour. Geol., 16, 1908, 193.

FIG. 17. SILLS IN VOLCANIC BRECCIA, MOUNT HESPERUS, COLO.

W. Cross, U. S. Geol. Surv.

Fig. 18. Volcano Mayon, Luzon

Bureau of Science, Manila

Bodies of crystalline rocks wherever found intersecting other rocks, that is, intruded in them, are solidified molten magmas, volcanic in the broadest sense. Those of great size and indefinite shape have been called batholiths and consist, commonly, of granites, diorites, gabbros, or of other phanerocrystalline rocks. Bodies intruded between stratified rocks in such a manner as to have their upper surface covered, originally, by a dome of arching strata are laccoliths, and consist in most instances of porphyries.

The granites and other intrusive rocks of New England and of the Middle and Southern Atlantic States are the results of volcanic activity in geologically ancient times, mostly in Paleozoic and pre-Cambrian periods. Later, in Triassic times, the basaltic lavas of the Connecticut Valley, New Jersey, and farther south poured out upon the surface and also intruded some of the sandstone strata. Since that time no volcanic lavas have been erupted in this part of the continent. In the western regions of the Rocky Mountains, the Great Basin, and the Cordilleras of the Pacific Coast, volcanic activity was violent in late Mesozoic times and throughout the Tertiary, producing long ranges of volcanic mountains and vast plains of extruded lavas.

At the present day active volcanoes occur along the Pacific Coast of South America, in Central America, Mexico, and the West Indies; along the southwest coast of Alaska, the Aleutian Islands, and in a chain from Kamchatka to New Zealand, in many scattered islands in the southern and central Pacific Ocean, and in the East Indies. They occur in Iceland, southern Europe, the Mediterranean and Asia Minor; in islands off the west coast of Africa, and in the Antarctic regions and southern Indian Ocean.

Volcanic activity is widespread throughout the earth, but has not occurred at any one time in all parts of it. Its location shifts during thousands and millions of years. It breaks out in new localities at widely remote periods, continues for untold ages, and eventually ceases; in some instances not to reappear in the same locality so far as our powers of observation go. In some regions it recurs again and again after eons of inactivity, as has happened in the British Isles.[29]

The problem of volcanism involves a consideration of the initiation of the act of eruption, its cause, the probable source of molten lavas and their passage through the outer portion of the earth; the maintenance of eruptivity with variable periodic violence, and lapses of quiet flow, or with lava columns nearly stationary for centuries and thousands of years; and finally its cessation, and the solidification of intruded lavas to great depths; its continued inactivity through geological eons, and in some cases its recurrence in the same region after many thousands or even millions of years.

[29] Geikie, A. *The Ancient Volcanoes of Great Britain,* London, 1897.

CHAPTER II

NEBULAR HYPOTHESES

In order to understand the Problem of Volcanism it is necessary to obtain as clear a conception as possible of the physical characteristics of the earth; conceptions that shift with changes in our knowledge of the relation the earth sustains to other bodies in the solar system, and other systems in the universe. Conceptions of the earth's physical characteristics also change with increasing knowledge of the structure of those outer portions of it which are within the range of our observation, and also with our understanding of the material of which this outer portion is composed; that is, the rocks of the lithosphere.

The most conspicuous characteristic of volcanism is the heated condition of the molten lava. A high degree of heat is involved in the production of igneous rocks. Intense heat has always been the most obvious factor conditioning volcanic action. The flow of incandescent material from the interior of the earth led early investigators to the immediate conclusion that the earth's interior consisted of similar molten liquid matter; and the increasing warmth of the earth downward from the surface, which has been measured in deep wells and mines, has confirmed the belief that the innermost parts of the earth are highly heated. But to the questions: How hot? and How heated? With what distribution of heat? and From what source? there have been no convincing, no concordant answers. For there can never be direct means of observation from the exterior of the

globe, and opinions on the subject must rest on conceptions of the origin and history of the planet. It is, therefore, essential to an understanding of the problem of volcanism that the theories regarding the origin of the earth be taken into consideration, so far as they affect conceptions of the source and supply of the most essential element in the discussion, the heat of the earth.[1]

Of the earlier speculations regarding the formation of the earth and the solar system which have a bearing on modern theories of volcanism, that of Descartes, enunciated in 1644, forty-three years before the publication of Newton's *Principia,* is interesting because it is one of the first to suggest that the earth might be a molten globe with a solid rocky crust. He attempted to develop the sun and planets from a system of vortices.[2]

All modern cosmogonies are based upon Newton's principles of universal gravitation, and may be considered as dating from the time of the appearance of his publication in 1687. But Newton's mind was occupied with explanations of the motions and mutual attractions of the parts of the solar system, and made no attempt to imagine the process of their evolution.

The first considerable hypothesis as to the origin of the planets and satellites, which must be considered as inseparable from modern theories, is that of the great French naturalist, Buffon. Accepting the conclusions

[1] In the preparation of this chapter the author has made use of papers by George F. Becker, on "Kant as a Natural Philosopher," Am. Jour. Sci., 5, 1897, 97; and on "Chamberlin's Origin of the Earth," read before the Washington Academy of Sciences, March 29, 1904; also Agnes M. Clerke's *Modern Cosmogonies,* London, 1905, and *Problems in Astrophysics,* London, 1903; H. Poincarée, *Leçons sur les Hypothèses Cosmogoniques,* 2d Ed., Paris, 1913; besides the publications specifically referred to in the text.

[2] Descartes, *Les Principes de la Philosophie,* Cousin's Ed., 1824, part 3, sect. 52.

Fig. 19 Lick Observatory

OWL NEBULA. M.97. URSAE MAJORIS

Fig. 20 Lick Observatory

RING NEBULA. M.57. IN LYRA

of Newton regarding the mutual dependence of the movements of the members of the solar system, he was so impressed with the conformities of the revolutions of the planets and their satellites about the sun, that he estimated the probabilities of the chances of their having been formed by independent operations, and found them overwhelmingly in favor of their having been produced by a single action, and not by independent ones.

In 1745 he suggested that a comet might have struck the sun, or have grazed its surface, driving off some of its material to which might be communicated a common motion, and that these parts driven outside the body of the sun and of the comet would become planets, which would revolve about the sun in like directions and in the same plane. He considered that it would require a very powerful comet, with great mass, traveling at a high velocity when near the sun. The material leaving the sun would form a torrent of particles that would eventually acquire elliptical motions like those of the planets, and that subsequently through their mutual attractions they would be aggregated into planets. In passing through the immense atmosphere of the sun, the ejected matter would draw with it volatile material which would become the atmosphere and water of the earth.[3]

At the time Buffon was describing and classifying all manner of living organisms, Immanuel Kant was lecturing on mathematics and physical geography at Königsberg. His education and interests placed him in a position to appreciate the advancements in astronomy, and grasp the application of Newton's principles to

[3] de Buffon, G. L. L., 1745. Reproduced in Œuvres complètes de Buffon et de ses continuateurs, Buffon et Daubenton, *Théorie de la Terre,* Bruxelles, 1828, vol. 1, art. 1, 110.

planetary systems. He was also acquainted with the physical features of the earth as then known and understood, and his philosophical temperament led him to imagine a process by which the parts of the universe might have been developed out of chaos. He argued that since the planets and their satellites moved in strict conformity with one another and in definite relation to a central sun, with vacant spaces between them, there must have been originally some material connection between them, without vacant spaces; that is, there must have been a diffusion of their substance through space, and a subsequent segregation into planetary masses.[4]

So he conceived of space as filled with particles highly varied as to mass, density, and power of attracting other particles. These were assumed to be elemental in nature, fundamental material, "Grundstoff." The average density of this diffuse system was far less than that of our atmosphere. It was without heat, and at the instant of the beginning of the conception was imagined to be without motion. But he remarked "space filled with matter so variously constituted could remain at rest only an instant," which is equivalent to saying that it could not exist without motion. It might be imagined at rest only in a mathematical sense, as a limiting condition for zero time. Elemental particles with the greatest density would occupy the least space, being the scarcest and most widely scattered.

The attractions of the particles for one another would occasion motion in all directions throughout the swarm. The denser would in time become nuclei of condensation. If there were but one preponderating nucleus he

[4] Kant, Immanuel. Sämmtliche Werke, Ed. by G. Hartenstein, Leipzig, 1868, vol. 1, 207-345, "Allgemeine Naturgeschichte und Theorie des Himmels," etc.

Fig. 21 Lick Observatory

DUMB-BELL NEBULA IN VULPECULA

Fig. 27 Lick Observatory

SPIRAL NEBULA, M 66, LEONIS

imagined that the conflicting elementary motions of the surrounding particles would eventually develop a preponderating circular motion of the swarm. Motions athwart this would be diminished and destroyed by collisions of the moving particles, which would finally yield to the attraction of the nearest nucleus. There would thus result zones or rings of discrete particles segregating into condensing nuclei, which, upon further condensation, become planets and satellites; the preponderating, central nucleus becoming the sun.

This suggestion, published in 1755, was a nebular hypothesis, offered in explanation of the origin of the solar system, forty-one years in advance of the first publication of Laplace's hypothesis. It attempted no mathematical demonstration, for as Kant stated in its introduction, "In general the highest geometrical precision and mathematical infallibility can never be demanded from a treatise of this description. If the system is founded on analogies and agreements developed according to the rules of credibility and in a logical manner, it satisfies the conditions which its object demands."

Kant's alertness to grasp the significance of observations in various fields of research and apply them to the most profound problems is well shown in his application of a discovery by Adair Crawford, professor of chemistry in the Woolwich Military Academy, that upon condensation gases liberate heat, a fact which was published in 1779 in an account of the first attempt to determine the specific heat of gases. Kant promptly applied it to the question as to the source of the sun's heat—"Woher kam die Wärme der Sonne?" inserting it in an article published six years later, in 1785, on the volcanoes in the moon; a discussion that had been precipitated by the

announcement of the discovery of a volcano on the moon by Sir William Herschel on May 4, 1783.

Kant wrote: "If one assumes that the elemental material of all celestial bodies was originally scattered in an attenuated condition throughout the whole vast space in which they now move, and that from this material they have been formed through cosmical attraction according to laws that are chiefly chemical, then Crawford's discovery gives a hint or suggestion which makes it possible to understand how with the formation of celestial bodies there may be developed at the same time as high a degree of heat as any one may desire."[5] For if the element of heat is uniformly distributed in space and is associated with different substances according to their attraction for it; and if, as Crawford has shown, thinly attenuated materials hold within them much more elemental heat in a highly distributed condition than they can hold when they pass into a condition of greater density, that is, into planetary spheres, then these spheres must possess more heat in proportion to their volume than surrounding space. The extent of this increase of temperature depends on the amount of the original attenuation, the degree of condensation, and the shortness of the time taken for the change. This depends on the strength of attraction that unites the scattered material, and this on the quantity of matter which is added to the growing world. So the amount of heating must be proportional to this growth. Consequently, the greatest heat will be in the central body, or sun.

This is a clear enunciation of the principle of the development of heat by condensation applied to the

[5] Kant, Immanuel. Sämmtliche Werke, vol. 4, 193-202, *Ueber die Vulkane im Monde.*

Fig. 23

Lick Observatory

TRIFID NEBULA M. 20 SAGITTARII

formation of the members of the solar system, a generalization usually credited to Helmholtz. In Kant's time, conceptions of the nature of heat were not those of the present day, and Lord Kelvin has remarked of Kant's hypothesis, "It only wanted the knowledge of thermodynamics to lead to a thoroughly definite explanation of all that is known regarding the present actions and temperatures of the earth, and of the sun and other heavenly bodies."[6]

With regard to the craters on the moon, Kant suggested that they are different from volcanic craters on the earth, and that similar huge craters may have been formed in the early history of the earth at a period when it might be thought of as a "chaos dissolved in water." The first eruptions, which must have arisen everywhere from great depths, would have been atmospheric in the proper sense of the word, for one may imagine that the atmosphere, that now covers the surface of the earth, was formerly mixed with the other materials of the earth's mass in a chaos; and that with many other elastic gases it broke forth in great bubbles from the heated sphere. In the ebullition, from which no part of the earth was free, the materials were thrown out in crater-like forms and constituted the earliest mountains. True volcanic eruptions in the present-day sense occurred later. This essay was written thirty years after that in which he discussed the origin of planetary systems.

In 1796, eleven years after Kant's essay on volcanoes on the moon, Laplace published the first statement of his nebular hypothesis as to the origin of the solar system, a second edition with modifications appearing in 1824. Laplace imagined the planets and satellites,

[6] Lord Kelvin. Address Geol. Soc. Glasgow, 3, 1869, 236.

because of the similarity in their rotations and in the planes of their orbits, to have been derived from some vast fluid atmosphere of immense attenuation which surrounded the sun. This nebulosity was supposed to have possessed a high temperature, and was so attenuated that one may scarcely conceive of its existence. It revolved about the central sun and assumed a disc-like form. In the course of time it separated into zones or rings that segregated into nuclei and eventually condensed into planets and satellites. To account for the eccentricities in the orbits and their deviations from one plane of revolution, he imagined that there were numberless variations in the temperature of different parts of the nebula and in the densities of the nuclei; that is, it was a nebula that was clearly heterogeneous both as to density and temperature. He made no specific statement as to the distribution of these heterogeneities, and did not attempt to apply his hypothesis in a quantitative manner to the mathematical requirements of the motions and masses of the parts of the solar system as then known.

He thought that the flattening of the earth's sphere at the poles of rotation indicated a former liquidity of the globe, and commented on the probability of changes of combination of all terrestrial substances on passing from a state of highly heated gases to one of liquids and solids. Evidently he conceived of the earth as having passed from a gaseous to a liquid, and finally a solid, condition. In his discussions of the tides and of precession he assumes that it possesses absolute rigidity. The whole hypothesis is expressed in few words and in very simple terms in the last of several notes appended to his great treatise, "Exposition du Système du

Fig. 24 Lick Observatory

NET-WORK NEBULA IN CYGNUS

Monde.'"[7] It is interesting to note that Laplace suggested at this time that groups of stars, especially the Pleiades, may have resulted from the condensation of nebulæ—a suggestion that has received support from the subsequent discovery of vast fields of nebulæ apparently associated with this great constellation.

A nebular hypothesis as to the origin of the solar system, and therefore of the earth, has come to be a widely accepted theory among geologists, who have restated it in various terms, in some instances with elemental simplicity and misleading terminology, not infrequently dignifying their invention by calling it the Laplacean hypothesis. The possible constitutions of nebulæ are among the most speculative of astronomical conceptions, as may be seen from a study of the varied observations and opinions of modern astronomers on the increasingly numerous clouds of these ghostly stellar mists; and it is misleading to attribute to so keen an astronomer as Laplace, who lived at a time when the nature of nebulæ was scarcely guessed at, geologists' formulæ, some of which are as crudely simple as the cogwheels of a mechanical toy. These commonly picture the earth as once a vast cloud of hot gas, which upon cooling became a liquid sphere intensely heated like the sun, and composed of mineral matter similar to molten volcanic lavas. Upon further cooling this is supposed to have solidified into the earth as we now know it. As to the process of solidification hypotheses differ widely. According to some, solidification commenced at the surface of the globe and progressed inward to a relatively small distance, the interior remaining liquid. Others have assumed that the pressure at the center of

[7] Œuvres Complètes de Laplace, Paris, 1884, vol. 6, 498, note vii.

the mass was sufficient to solidify matter at an extremely high temperature, causing the central part to be solid with a surrounding shell of liquid, and an outer crust of cooled matter. According to other hypotheses, solidification has taken place throughout the whole of the globe.

In 1862 Lord Kelvin called attention to the fact that the earth is more rigid than a solid globe of glass of the same diameter, and probably than one of steel.[8] The possible effect of the tidal action of the moon's attraction on a liquid globe having the mass of the earth has been investigated mathematically by Sir George Darwin and found to be so much greater than the effect actually observed that it is necessary to conclude that the earth is not a viscous liquid, but possesses a very effective rigidity, like that of steel.[9] In order to conform to this astronomical requirement, then, it appears to be necessary to assume a condition of the material of the earth such that it may behave toward outward attractions as if it were a solid mass, whatever may be its temperature, or physical phase, or state.

This demand for a rigid earth has led to the conception of its possible development from discrete solid particles or meteorite-like bodies. The possible behavior of swarms of such masses has been discussed mathematically by Sir George Darwin, who treated them as though they possessed some of the qualities of gaseous matter, having elasticity and gaseous viscosity.[10]

However, since the impact of meteoric bodies traveling with high velocities would produce gas, and would also

[8] Lord Kelvin. *On the Rigidity of the Earth,* Roy. Phil. Soc. of London, 1862.

[9] Darwin, G. H. Phil. Trans. Roy. Soc. London, 1879, part 1, 1.

[10] Darwin, George H. Phil. Trans. Roy. Soc. London, 1888 (1889).

Fig. 25 Yerkes Observatory

GREAT NEBULA IN ANDROMEDA

destroy their own motions, his conclusions appear to be inapplicable to the case of true meteorites, which do not react on one another like molecules of a gas. Maxwell has discussed the behavior of the discrete parts composing the rings of Saturn, and has considered the possibility of their segregating into satellites about the planet.[11] Lord Kelvin is said to have expressed the opinion many years ago, "that the most probable origin of planets was through a gradual accretion of meteoric matter."[12] The formation of planets and satellites by the aggregation of discrete particles moving in elliptical orbits about a central body is essentially the conception of Kant, as already noted.

On a basis of supposed similarities between the spectra of the various heavenly bodies and those obtained from meteorites, Sir Norman Lockyer suggested the hypothesis that the solar system, the stars and nebulæ might all be derived from the impact, volatilization, and aggregation of meteoric bodies.[13] However, it is to be noted that there are no metallic lines in the spectra of nebulæ.

In an attempt to solve the problem of glaciation and the production of great areas of ice on the globe in widely remote geological periods, quite a different problem from that of volcanism, and in an endeavor to discover the sources of the gases of the atmosphere, Professor T. C. Chamberlin was led to review the hypotheses respecting the origin of the earth chiefly with the conviction that a highly heated liquid globe having the mass of the earth would not be able to retain light gases, such as hydrogen, whose molecular velocity at such temperatures would

[11] Maxwell, J. C. Scientific Papers, I, 288.

[12] Stated by Sir George Darwin in 1888 in Phil. Trans. Roy. Soc. London, 1888 (1889).

[13] Lockyer, Sir Norman. *The Meteoric Hypothesis,* London, 1890.

carry them beyond the gravitational attraction of the mass.[14]

Moreover, the geologist's conception of a nebula of homogeneous gas revolving about a central nucleus and separating into annular zones that were supposed to condense into the planets and satellites of the solar system has been shown by F. R. Moulton to be incompatible with the requirements of the principle of the moment of momentum, because of the various masses and rates of rotation and velocities of revolution of the several planets and satellites.[15]

Chamberlin therefore considered the material composing the nebula as behaving, not like a gas, but as though composed of discrete particles moving in orbits around a central gaseous mass or nucleus, the orbits being elliptical, with slightly different eccentricities and planes of revolution. These particles he calls planetesimals because they have motions similar to those of the planets, not from any resemblance in substance, for regarding their substance he makes no assumption, remarking, "they may be molecules, or small masses of any kind," that is to say, in any phase, solid, liquid or gaseous; but gaseous matter is supposed to have been subordinate to solid or liquid matter, for he considers that molecules moving in all possible directions, as in a gaseous condition, would dissipate in space until they encountered particles moving in the planetary orbits whose mass was sufficient to attract and hold them. The fundamental concept in this hypothesis is the character of the motion of the discrete particles composing the revolving nebula. They move individually in elliptical orbits about a nucleal focus. Their motion is not that

[14] Chamberlin, T. C. Jour. Geol., 5, 1897, 653.

[15] Moulton, F. R. Astrophysical Journal, 2, 1890, 114; 11, 1900, 115.

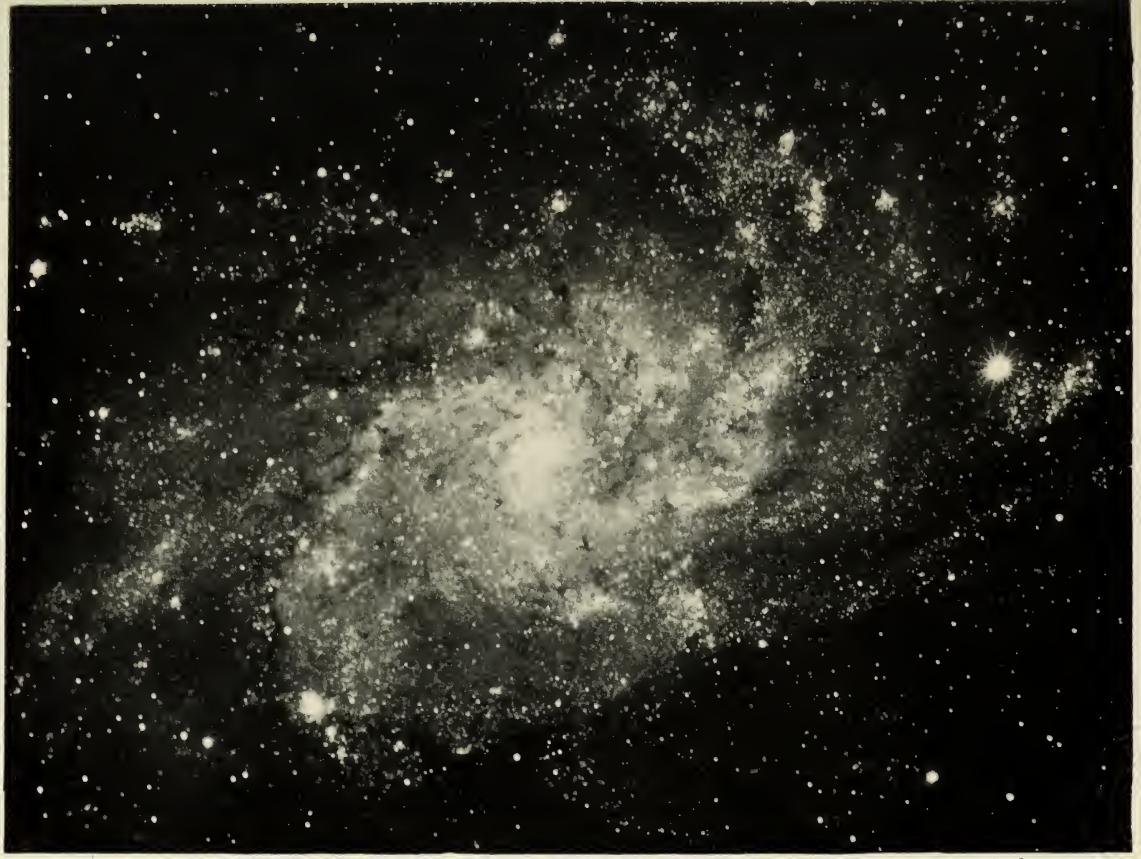

Fig. 26 Lick Observatory

SPIRAL NEBULA M. 33 TRIANGULI

of gas molecules, in all possible directions. Consequently, though the particles may be molecules, they do not behave as a gas, and their condensation and impact would not be like those of gas molecules. If the particles be aggregated molecules, in solid phase, they would not have the motion of meteorites as now encountered by the earth, but would have the motion of planets within the solar system.

This assumption corresponds to that of Kant after his chaos of particles had acquired elliptical motion about a central nucleus, and after aggregation had commenced. It is based chiefly on the kinetics of the problem, attempting to account for the aggregation of particles moving swiftly in nearly parallel orbits, and the production of direct rotation by a proper adjustment of eccentricities and velocities of the several particles. In order to satisfy the conditions of the diverse masses and revolutions of the different planets of the solar system a heterogeneous distribution of nebulous matter appears to be necessary, and this is characteristic of many spiral nebulæ. This condition was probably anticipated by Laplace before telescopic photography revealed the marvelous details of the greater nebulæ, when he referred to the numberless varieties which must exist in the temperature and density of different parts of the great masses that were supposed to have composed the solar nebula. Upon seeing a very remarkable photograph of the great spiral nebula in Andromeda, Sir George Darwin wrote, in 1888, that it afforded "something like a proof of the substantial truth of the nebular hypothesis."[16]

Hypotheses that postulate a chaos of discrete particles which develop rotary motions about nuclei have been

[16] Phil. Trans. Roy. Soc. London, 1888 (1889).

suggested by H. Faye,[17] who imagines the formation of clouds that acquire vortex motions and resemble spiral nebulæ, and by R. du Ligondès, who assumes sufficient initial motion in all directions to be eventually resolved into the required moment of momentum for the maintenance of the solar system.[18]

An insight into the possible constitution of nebulæ that have been studied since the application of photography and the spectroscope to stellar research, may be obtained by a review of some of the results of investigations in these fields,[19] for spectroscopic observations furnish the only means of learning anything of the material character of nebulæ. So far as these go they indicate that there are two categories of nebulæ, one group being characterized by bright spectral lines as though the nebulæ were incandescent gases in great part, the so-called "green" nebulæ; the other group showing continuous spectra, with quite subordinate bright lines in some cases. These are known as "white" nebulæ.

The gases recognized by their spectra in the first group are chiefly hydrogen, helium, and nebulium, an element not yet found upon the earth, or in the spectra of the sun or stars. It is characterized by clear green lines, and is probably somewhat denser than hydrogen, since its area of diffusion appears to be less than that of hydrogen in the great irregularly shaped nebula in Orion. The number of gaseous nebulæ is comparatively small. They are known as nebulous stars, planetary nebulæ, annular or ring nebulæ, and irregularly shaped cloud-like nebulæ of vast extent.

[17] Faye, H. *Sur l'origine du Monde,* Paris, 4th Ed., 1907.

[18] Ligondès, R. du. *Formation mécanique du Système du Monde,* Paris, 1897.

[19] Clerke, Agnes M. *Problems in Astrophysics,* London, 1903.

Fig. 28 Lick Observatory

SPIRAL NEBULA, M. 61. VIRGINIS

Fig. 29 Lick Observatory

SPIRAL NEBULA, M. 51. CANUM VENATICORUM

Planetary nebulæ are markedly elliptical in most instances, their form being spheroidal. Their mass is obviously tenuous, some appearing to be surrounded by a filmy mist. They appear to rotate very slowly. The planetary nebula in Ophiuchus has been resolved by Vogel into three distinct layers, which are thought to indicate the effusion of matter from the central portion at three periods, the intervals between which may have been ages long. This appearance is typical of many nebulæ of this kind. The largest planetary nebula, known as the "owl nebula," is located near the second pointer of the Great Bear (Fig. 19).[20] It consists of a central nucleus, which has been visible and invisible to telescopic observers at different times, but appears photographically persistent. There is a large central dark space and an outer filmy rim. The pale bluish light from this nebula is not more than one four-millionth that of white-hot iron.

A fine example of an annular nebula is situated in Lyra (Fig. 20). It appears to consist of several narrow, bright rings which interlace somewhat irregularly, the spaces between them being filled with fainter nebulosity. The central spot has been quite variable, disappearing at times. There are radiations, fringes or tufts, which also appear to be variable, and extend outward in the plane of the equator, that is, in the line of the longer axis of the image, which is 64″ by 87″ in angular dimensions. Its probable size may be estimated from the assumption by Newkirk that the central nucleus is so distant that its light would take thirty-two years to reach the earth, a distance of two hundred million million miles! Since

[20] The accompanying illustrations of nebulæ have been generously furnished by the Lick Observatory, with the exception of one kindly furnished by the Yerkes Observatory.

the angular diameter is about one minute, the radius of the nebula would be about three hundred times that of the earth's orbit, something like twenty-eight thousand million miles. A planetary nebula with circular image and an outer zone of more attenuated matter occurs in Pegasus. Its apparent spherical form may be due to its position, since most others are flattened spheroids. Another form of gaseous nebula is shown in the Dumb-bell nebula in Vulpecula (Fig. 21). It is a flattened spheroid about 8′ in diameter, with concentration of matter in opposite parts in the direction of the shorter axis. There are indications of marginal shells of condensation, besides emanations of faint luminosity in the equatorial plane. It exhibits some resemblance to the annular nebula in Lyra, and its mottled ill-defined areas have some affinities with irregular cloud-like nebulæ.

The most immense area of nebulæ occurs in association with the Pleiades. This group of more than forty-five stars is the center of nebulous matter in irregularly shaped clouds covering at least one hundred square degrees of the heavens, according to Professor Barnard. A genetic connection between the stars of this constellation and the surrounding nebula is thought to be probable by some astronomers, and such an origin was suggested by Laplace before the discovery of the nebula. A great cloud-like nebula is situated in Orion (Frontispiece, Fig. 22). Its streams of luminous matter spread like a flame through a semicircular arc. The vastness of its size may be imagined from its possible distance, which Professor Pickering has estimated at one thousand light years, that is, over six thousand million million miles. Spectroscopic study has shown that the distribution of nebulium and hydrogen is not uniform throughout its great expanse, that it is to this extent heteroge-

Fig. 30 Lick Observatory

SPIRAL NEBULA. M 101 URSAE MAJORIS

neous, and that hydrogen is the more widely diffused of the two elements. Another wonderful cloud-like nebula is the Trifid in Sagittarius (Fig. 23). Clouds of luminous matter are separated by rifts of darkness whose character is unknown. A somewhat more expanded nebulous cloud also occurs in Sagittarius. Another great cloud-like nebula of this kind is the "network" nebula in Cygnus (Fig. 24). It appears like a cirrus cloud of inconceivable extent, stretching through a degree and a half.

Gaseous nebulæ are almost perfectly transparent; their substance is so extremely attenuated that it has been estimated by Raynard that the rarefaction in the nebula in Orion is one ten-thousand-millionth that of our atmosphere at standard pressure. Their mass is immeasurably small compared with their volume. The radius of spheroidal planetary nebulæ is seldom less than fifty to sixty thousand million miles, often much greater. It may be questioned whether matter in such attenuation may exist in gaseous phase, or may be in discrete particles as postulated by the accretionary hypothesis. A. Schuster,[21] in his discussion of the evolution of solar stars, has suggested that cloud-like nebulæ may consist of the lighter gases, hydrogen and helium, which may have been given off from the stellar nuclei when these possessed too high a temperature and too low a density to retain such gases; and that subsequently these gases may be absorbed by the stellar bodies when their density and temperature permit the gases to be retained. Gaseous nebulæ shine with extreme feebleness, which is as faint as it appears, since remoteness of objects in space does not affect the intensity of

[21] Schuster, A. Astrophysical Journal, 17, 1903, 165.

the light emitted by them. The cause of their luminosity is unknown. It is probably not due to heat. Hydrogen and helium gases only exhibit spectra when excited electrically, and Scheiner has found that the spectrum of hydrogen is unchanged when a hydrogen tube is inserted in liquid air and its temperature reduced to — 200° C. The light emitted may be due to electric discharge, and the temperature of such nebulæ may be near absolute zero. A similar opinion was entertained by H. Poincarée, who considered it to be the general one at the present time.[22]

The "white" nebulæ, with continuous spectra, form by far the largest number of these diffuse systems. They are mostly spiral in structure, with an elliptical shape in many cases. Professor Keeler found the number to be about 120,000, nearly all of which were spiral. Subsequent work with the same instrument, the Crossley reflecting telescope, has shown that the number which may be discernible by the use of more sensitive plates and longer exposures is of the order of magnitude of 500,000.[23] Still more recent observations place this number at more than a million.[24] The apparent size of these objects varies greatly, the greatest and probably the nearest is in Andromeda and is visible without a telescope. Its form is elliptical, the nucleal portion being spherical. It appears to be a nearly circular disc tilted about 25° to the line of sight. The nebular matter is scattered irregularly throughout broad bands which are coiled around the central portion, the condensation being greatest within, the outermost parts being thin and more

[22] Poincarée, H. *Leçons sur les Hypothèses Cosmogoniques*, Paris, 1913, lxii.

[23] Publications of the Lick Observatory, vol. 8, 1908.

[24] Perrine, C. D. Astrophysical Journal, 20, 1904, 356.

Fig. 31 Lick Observatory

SPIRAL NEBULA H. V. I CETI

scattered. The spiral arrangement of the arms is not so pronounced as in some other nebulæ of this class. The accompanying photograph (Fig. 25) was taken with the two-foot reflecting telescope at the Yerkes Observatory during a four-hour exposure.

A spiral structure is better shown in a nebula in Triangulus (Fig. 26), in which the luminous substance is quite unsymmetrically distributed about the nucleus, but suggests two principal arms starting from opposite sides of the center, and not coiled very much. Thin wisps of matter are in spiral positions in the marginal parts of the nebula. A more compact nebula in Leo (Fig. 27) shows a closer coiling of the streams, and small nodular lumps that are most marked on opposite sides of the central mass. A small spiral nebula in Virgo has some resemblance to a ring nebula (Fig. 28), the principal arms being coiled almost in a circle about a central star-like nucleus, but the ends of the more condensed parts of the arms extend in opposite directions from the circular zone, and are continued in faint arcs far beyond. The most remarkable spiral nebula occurs in Canes Venatici (Fig. 29). The coiled arms are distinct, and the largest is visible for an arc of 450° about the nucleus; the other for more than 360°. The nebular disc is normal to the line of sight. A secondary nucleus terminates the longer arm. There are minor nuclei scattered along the arms, from which wisps of matter curve outward and backward, in conformity with the direction of the coil. A spiral nebula in Ursa Major (Fig. 30) shows a more branching character to the arms, which have the appearance of being more than two. They are closely coiled about a small nucleus, and contain many scattered minor nuclei.

Some "white" nebulæ are narrow elliptical bodies,

apparently flattened nebular discs viewed nearly edgewise, having a mottled and streaked structure that suggests a spiral arrangement like those just described. A nebula of this shape occurs in Cetus (Fig. 31). It contains many minor nuclei, or knots, and has an indistinct bilateral arrangement. A beautiful nebula of this type is situated in Coma Berenice (Fig. 32). It is extremely narrow for its length, and possesses a spheroidal nucleus, which is traversed by a dark rift like a shadow of the thin disc upon the central spheroid. Another nebula of this character in which the dark rift is central occurs in Andromeda.

It is characteristic of spiral nebulæ that they consist of two or more arms wrapped about a center in which they meet, or from which they may be said to extend. A nebula in which two arms are clearly shown as narrow trains of luminous matter occurs in Pegasus (Fig. 33). The arms are as wide as the nucleus where they leave it, one of them tapering to a very narrow stream, the other splitting into two faint streams. Each arm curves back around the nucleus in an arc of 180°. A similar, but less definite, form of this type of nebula occurs in Virgo, and is shown in Figure 34. Its arms have not closed in about the central nucleus as in the previous case; the spiral appears not to have revolved as far. The material in the arms is irregularly distributed and not uncommonly is segregated in nebulous knots or clouds.

As to the cause of the light of the so-called "white" nebulæ nothing is known, and opinions differ as to their elemental constitution. They may consist of discrete particles, or as Sir Robert Ball has expressed it, of "pulverulent material." Many spiral nebulæ have a far greater expanse than the solar system. No motion has been observed in any of them up to the present time,

Fig. 32

Lick Observatory

NEBULA H. V. 24. COMAE BERENICES

but it is to be remembered that detailed photographs of them have been obtained only recently, so that there are no reliable records of any considerable age from which to note changes in their position, if any are taking place. However, the spiral arrangement of the parts clearly indicates a rotary motion about a center, which appears to have the greater angular velocity, judging from the shape of the spirals.

In seeking a cause for the spiral arrangement of these nebulæ, the position of the arms on opposite sides of the center has suggested the possibility of an explosion of some central mass, and recourse has been had to the principle enunciated by Roche that the near approach of one great mass to a lesser one within a distance that is 2.44 of its mean radius, now known as Roche's limit, would disrupt the smaller mass, since the approach of a mass of equal or greater magnitude would reduce the gravitational attraction within the second body along the line of mutual attraction between the two, proportionately increasing the force of gravity at right angles to this direction. If the smaller mass were a gaseous body like the sun, which by observation is known to possess such explosive energy that it projects jets of its substance thousands of miles from its surface at velocities greater than 300 miles a second, then the near approach of a larger mass might cause a series of pulsating explosions, projecting from opposite sides of the sun portions of its substance, which would travel with such velocities that they might pass beyond the limit of immediate radial return to the sun's body; and having acquired a tangential impulse from the grazing mass that caused the disruption would travel in resultant orbits about the sun. The mass of the solar system now revolving around the sun is about one seven-hundredth

of the mass of the whole system, so that the amount of matter assumed to have been ejected in this manner is not excessive. Since the body of the sun has different densities at different distances from its center, and contains different substances, it may be assumed that the outer portions consist mostly of lighter materials, and that explosions affecting different depths would liberate material with different average densities, resulting in an assemblage of substances in the projected jets that would be heterogeneous both as to the proportions of kinds of substances, and as to the closeness of their aggregation.

According to the kinds of elements or compounds that are assumed to have been projected in a gaseous condition, and the changes in temperature that may be assumed to have accompanied their change of place, there would result solid, liquid or gaseous phases of the discrete particles. This hypothesis will be recognized as a refined expression of the conception of Buffon. The fundamental ideas are alike, the modern expression of it has had the advantage of a hundred and fifty years of astronomical discoveries and of improvements in the physical sciences.

In his discussion of the possible development of planets and satellites from a spiral nebula of such an imagined constitution, Professor Chamberlin points out three essential factors: a central mass to become a sun; cloudy knots to become nuclei of planets; and scattered nebulous matter to be added to the nuclei of the planets or to be added to the sun. In order to correspond to the present distribution of mass and energy in the solar system the central mass should be overwhelmingly large; the nucleal clouds should be quite different in size and very unequally distributed about

Fig. 33 Lick Observatory

SPIRAL NEBULA. H I 55. PEGASI

Fig. 34 Lick Observatory

SPIRAL NEBULA. H V 2. VIRGINIS

the center; moreover, the mass of the scattered nebulous matter should be small with reference to the sun, but relatively large with respect to the nucleal clouds. In this discussion gases are treated as though they were coherent entities to be captured by attraction and inclusion or occlusion within solid or liquid masses, or else lost by dissipation into space. It is equally proper to imagine such dissipated wandering molecules being picked up by the superior attraction of more substantial matter, to be incorporated by combination or absorption according to the chemicophysical equilibrium under which the system then existed, and that subsequently these molecules may appear in a gaseous state if the conditions are favorable for their so doing. It is then immaterial whether certain elements or compounds which occur upon the earth at present in a gaseous phase were in this condition when nebular, or were in fixed compounds, or in discrete molecules, atoms, or electrons, since the material constitution and temperature of nebulæ are at present wholly matters of speculation.

The possible process of aggregation of nebular material into a planet is variously imagined according to the assumed temperature of the nebular body, the mass of the discrete parts, and the rate of aggregation. Earlier hypotheses assumed so high a temperature that the planetary masses would be gaseous, or molten liquids surrounded by gases. On the hypothesis that the earth was formed by the aggregation of solid particles, or of the indefinite solids and liquids suggested by Professor Chamberlin, it has been assumed that the swarm would have a temperature below the solidifying points of the less fusible substances and above the melting points of the more fusible ones, and that the rate of accretion of material would be very slow at first, increasing with the

increase of mass of the nucleus up to a stage in which the supply of material would decrease because of its increasing distance from the nucleus.

With increasing momentum of the infalling particles of impact, which depends upon the mass of the nucleus, the mass of the attracted particle, and the distance through which it travels, there might be increase in the heat generated at the surface of the globe by reason of the arrested motion. The extent to which the temperature of the globe would be affected will depend upon the specific heat of the colliding substance, which would absorb some heat if there were a change of molecular condition or of phase; also upon the heat conductivity of the surficial material of the growing nucleus, and upon the frequency of impact.

The elasticity of this hypothesis is immense, the imagination is unrestrained and has been exercised at both extremities of the range of possibilities, for at one end of the reach is the very perceptible sun, and at the other the almost imperceptible, but impressive, nebulæ. In the sun we appear to have an example of condensation with the evolution of tremendous heat, enormous ebullition of gaseous molten liquids, embodying most of the elements known upon the earth. This is held by many to be the prototype of the planets in their early stages of development, and in particular of the earth. It is one extreme of the many possibilities of the nebular hypotheses from the earliest to the latest.

At the other extreme of the range of rates of change of imagined aggregation are the nebulæ themselves, vast, diffused, and apparently motionless; enormous in their extent in space, enigmatical in their substance, and so distant that the arc of their conceivable angular motion has not yet had time to disclose itself, owing to the

shortness of our acquaintance with them. They appear to be the embodiment of static energy on an almost inconceivably gigantic scale; to be an illustration of static equilibrium. They appear to be, for this view may possess an enchantment lent by distance, the element of time being necessary to disturb the apparent static equilibrium, for we have only to reflect upon the velocity with which we are being whirled headlong about the axis of this globe, to say nothing of the speed with which the earth and ourselves are traveling through space, to become convinced that there may be equilibrium of motion, and that the more intimately we are acquainted with celestial bodies the more active their energies appear to be. Nevertheless, as Chamberlin has expressed it, "The one thing, perhaps, above all other things, which the progress of research is bringing into recognition is the immensity of the energy of the universe, of which energy only a small fraction is usually apparent to us, doubtless because it is chiefly in a state of equilibrium, and only becomes sensible when its equilibrium is disturbed."[25]

It is possible that accretion of nebular particles may progress at such a rate that the temperature of the surface of the growing sphere is not raised by the process, and that the material added experiences no change of state while at the surface of the sphere, whatever may happen to it when it becomes buried beneath an increasing load of fallen particles. This seems highly reasonable if the time occupied in growth is of the same order of magnitude as the nebular space involved, and is in any way reciprocal to the size of the discrete particles when compared with that of the completed

[25] Chamberlin, T. C., and Salisbury, R. D. *Geology,* New York, 1906, vol. 2, 52.

planet. Langley has estimated that one hundred tons of meteoric matter is being added to the earth daily, but its heating effect is imperceptible to us.

Such an assumption as to the heating effect of aggregation is made by Chamberlin in his hypothesis as to the growth of the earth. There remains, however, the crucial doubt as to the possible temperature of the nebula and the initial heat of the nucleal earth, which was recognized by him when he discussed the sources of the present heat of the earth, and remarked that "The young earth, or nebular nucleus, may have inherited a hot nucleus." The question immediately suggests itself, How hot?

Under the assumption that a spiral nebula may be an exploded sun, a nucleal cloud must differ from the substance of the sun from which it escaped chiefly through loss of heat and lessened pressure, and whatever physical changes these may impose on its substance. Chamberlin considered it possible that the nucleus might have consisted for the most part of heavy molecules of metallic and mineral substances, such as form rocks, and become liquids and solids at high temperatures, and he suggested that the movement of these particles might be similar to that of a gas, and upon condensation evolve heat. Further, that whatever the sum of this early nucleal heat and the inherited nebular heat, there would be a further accession of heat from the continued condensation of the growing planet, due to its increasing mass; and probably from molecular rearrangement of elements which had combined under slight mutual gravitation or pressure, and would undergo molecular readjustment, conditioned by changes of pressure arising from increasing load with increasing size of the planet, which molecular change should be accompanied by a liberation

of heat. He remarks that it is only necessary to postulate sufficient shrinkage in the volume of the sphere to obtain an internal temperature sufficient for all the requirements of volcanism.

The distribution of temperature throughout the globe, due to the heat of condensation under the action of gravitation, should differ from its distribution under the assumption of a cooling liquid sphere, since maximum pressure exists at the center. However, the rate of growth of the globe, and the rate of diffusion of heat within it, modify greatly the distribution of temperature within its mass, not only during the period of growth, but through the millions of years that have elapsed since it acquired its maximum size.

That the size of the bodies falling together during the growth of a planet may be more than those of small particles, or of any meteorites with which we are acquainted, is within the possibilities of the hypothesis itself, and finds very substantial support from several groups of phenomena, both astronomical and geological. According to the hypothesis, nebular particles are attracted to the nearest nucleal cluster, whatever its size, and when the larger have attained sufficient mass they will attract the smaller ones that are within their reach. These captured nuclei, or bodies, may fall to the surface of the larger nucleus or may rotate about it as satellites. If these satellites are very small and very numerous they may surround it in a belt like the rings of Saturn; if few and of considerable size they may revolve around it like the eight satellites of Jupiter; or if single they may be as the moon to the earth.

The effect of the fall of relatively large bodies to the surface of a growing planet may possibly be shown by

the surface of the moon, as suggested by G. K. Gilbert,[26] or on a smaller scale by the crater-like pit in Arizona at Coon Butte, which Gilbert suggested may have been produced by the impact of a large meteorite, a theory which subsequent investigations have shown to be highly probable, according to G. P. Merrill and Elihu Thomson.[27] This circular depression in sedimentary strata is about 600 feet deep and three-fourths of a mile in diameter; is surrounded by blocks of limestone and sandstone of all sizes, intermingled with particles of meteoric iron, and beneath the floor of the pit the sandstone is crushed into minute fragments to a depth of 600 feet. No volcanic lava is associated with this crater, although ancient volcanoes abound in the neighborhood. The conclusion seems warranted that the pit resulted from the impact of a large meteoric body, the material of which has mostly disappeared. A stone meteorite weighing 660 pounds penetrated the earth to a depth of eleven feet at Knyahinya, in Hungary, forming a circular pit four feet in diameter and four and one-half feet deep.[28]

The pits on the moon differ greatly from ordinary volcanic craters on the earth, chiefly by reason of their gigantic size and very uniformly circular shapes, and great abundance in proportion to the area of the moon's surface (Fig. 35). They are generally sunk below the level of the surrounding plain, and are not raised above it at the summit of cones as is the case with most volcanic craters, a good example of which is shown in Figure 36. Similar conical mountains with craters at their summits

[26] Gilbert, G. K. Science, 3, 1896, 1.

[27] Merrill, G. P. Smithsonian Miscellaneous Collections, 50, 1907. Thomson, E. Proc. Am. Ac. Arts and Sci., Boston, 47, 1912, 721.

[28] Haidinger. Sitz. d. k. Akad. Wiss., Abth. B. 54, 1866.

FIG. 35. LOWER QUARTER OF THE MOON

Lick Observatory

are not present on the moon, and flows like streams of molten lava have not been recognized. Other important distinctions have been pointed out by Gilbert,[29] who has called attention to the similarity between the lunar craters and depressions made in wet plaster or mud by falling bodies, and has argued that the craters on the moon were made by the impact of captured satellites of various sizes, and that their accession was the last considerable act in the moon's growth. The marvelous record has remained unimpaired through countless ages because there were no atmospheric waters to erode, and not enough internal heat to produce volcanic eruptions, or to bring about dislocations of the outer portions of the moon's sphere by shrinkage due to loss of volume through cooling, conditions which might be expected to obtain if the craters of the moon were explosive, and if they had been produced in the manner suggested by Chamberlin, who imagined that in the early stages of the earth there may have been an outer porous elastic zone, composed of various sized particles without cementing or adhering characters, there being no hydrosphere or atmosphere; and that if molten matter from within the planet found its way into this zone and gave off gases, more or less concentrated and condensed, they might force an exit to the surface by blowing away the overlying fragmental material, producing a pit-like crater of extraordinary magnitude, perhaps, as on the moon.[30] This speculation as to the formation of craters like those on the moon bears a striking resemblance to the suggestion of Kant, allowance being made for perspective. Internal heat sufficient to produce such craters

[29] Gilbert, G. K. "The Moon's Face," Bull. Phil. Soc., Washington, 12, 1892, 241.

[30] Chamberlin and Salisbury. *Geology*, New York, 1905, vol. 1, 597.

by gaseous explosion may be expected to lead to their subsequent obliteration through the shrinkage of the sphere upon cooling, if not by further eruption of lavas and the formation of cinder cones.

It has been suggested by Reyer that the moon's craters were produced by the escape of gases dissolved in the liquid globe, like the escape of oxygen gas from liquid silver at the moment of solidification.[31] But it can not be assumed that the moon's substance is metallic, or was possessed of such liquidity and heat conductivity if ever molten, or that solidification would take place with great rapidity in a body of such volume, or from within outward, leaving the exterior to solidify last. The moon's substance is probably stony, having an angle of polarization like that of obsidian;[32] and so far as observed, volcanic lavas do not spout forth gases upon solidification like silver.

From the foregoing we may conclude that a nebular hypothesis as to the origin of the earth does not at this time furnish any basis for a determination of the temperature of the inner portion of the earth; and that it can not be expected to do so until our knowledge of the physical characteristics of nebulæ is more definite, and the process is clearly understood by which they condense to form planets, if in fact such condensation takes place.

Opinions as to the temperature of the innermost parts of the earth are purely speculative extrapolations on an imaginary curve, imperfectly known for a distance of only one four-thousandth of the radius of the earth, and to a temperature of only 75° C., though a temperature of at least 1500° C. may be reasonably assumed to exist

[31] Reyer, E. *Beitrag zur Physik der Eruptionen*, Vienna, 1877.
[32] Landerer, M. *Comptes Rendus*, 111, 1890, 210.

FIG. 36. CINDER CONE NEAR SAN FRANCISCO MOUNTAIN, ARIZ.

G. K. Gilbert, U. S. Geol. Surv.

in the region of the source of volcanic lavas, that is, somewhere on the curve of earth temperatures far beyond our range of observation. Temperatures above this are purely imaginary and may, or may not, exist within the earth.

As to the opinion commonly held that the earth was once liquid, like the sun, a nebular hypothesis as to its origin does not necessarily demand it, and there is no evidence upon the surface of the earth itself that it ever was in a liquid condition. There are no rocks exposed which could be considered as originally solidified portions of a once liquid globe, and its spheroidal shape is consistent with the assumption of its present rigidity.

It seems reasonable to assume that nebulæ are not highly heated; that exploding and expanding matter, if finely divided and distributed through an enormous space, would cool far below its former temperature, if derived from a disrupted sun; that subsequent aggregation would be a very gradual process, and that whatever heat were generated by impact would be dissipated without considerable rise of temperature; that the heat of condensation might be a principal source of internal heat in a globe so formed, but that its amount would be greatly modified by the size and mass of the aggregation, the physical characters of its components, and by the time occupied in its growth.

CHAPTER III

PHYSICAL CHARACTERISTICS OF THE EARTH

The occurrence of volcanic activity in modern times in particular regions of the earth, around the borders of the Pacific Ocean and in chains of islands in its southern half, in scattered islands in the Atlantic and Indian oceans, in parts of the Mediterranean Sea, and elsewhere, as well as the absence of active volcanism from great areas of the continents and from certain parts of the oceans, and the occurrence in the continental regions of abundant evidences of extensive volcanic activity in earlier times, raises the question as to whether there are any relations between the location of volcanic outbreaks and the configuration and structure of the earth's surface; and the further question as to what extent the physical characteristics of the exterior portion of the earth may throw light upon the problem of its physical character at considerable depths, where the source of molten lavas may be reasonably considered to be located.

In order to attempt to answer these questions it is necessary to have in mind the salient features of the earth's exterior, both its form or topographic relief, and the structure of its outer zone of rock; that is, its present configuration and the results of the movements that have taken place within the lithosphere during those periods of its geological history of which we have any records. The form of the earth is well known to be a

flattened spheroid of rotation, the difference between the polar and equatorial radii being about 13.5 miles, or $\frac{1}{293}$ of the major radius of 3,963 miles. On a globe ten feet in diameter this difference in radii would be about 0.2 of an inch. The earth is essentially a sphere, and when its volume of 260 thousand million cubic miles is taken into account, and its mass of 6,000 million million million tons is thought of as whirling in space with an equatorial velocity of nearly seventeen miles a minute, this slight distension is quite in accord with our conception of a rigidity like that of steel.

The actual equatorial circumference of the earth, however, is not strictly a circle, and the earth's surface is not a uniform surface of rotation. Continents and mountain ranges rise above the surface of the oceans, and the solid earth at the sea bottom is much farther below this level than it is above it as dry land. The maximum difference in relief is about 61,115 feet, or about 11.5 miles, nearly the difference between the polar and equatorial radii. On a ten-foot globe this would be about 0.17 of an inch, but the differences throughout the greater part of the area might be represented by less than 0.05 of an inch on such a globe. These inequalities of surface, so great when viewed from the standpoint of a human observer, and so inconsiderable when compared with the volume of the whole earth, conform to the physical status of the substance of this huge sphere. Do they indicate homogeneity or heterogeneity of its substance? and if they correspond in any manner to some degree of heterogeneity, what may be its order of magnitude? Heterogeneity of mass, of a very high order volumetrically, is a necessary condition when the density of the whole earth, about 5.527, is compared with the density of the known portions of the lithosphere,

which may be about 2.75. The central part of the earth must be denser than the average for the earth as a whole. Variation in density from the center to the surface downward is a fundamental conception with respect to the mass of the earth, but it is commonly expressed in such a manner as to convey the impression that the variation is uniformly distributed in concentric zones, which are themselves homogeneous. That is, a heterogeneity that is radial only. Do the major inequalities of relief of the earth's surface indicate heterogeneity of its mass laterally as well as radially?

The mountains and plateaux, valleys and plains of the continents being much in evidence are familiar to us, and their general distribution and relative elevations are matters of common knowledge. The situation of the lofty chain of the Andes with peaks 18,000 and 23,000 feet in altitude within 100 miles of the sea coast is well known. The less lofty Cordilleras in North America, with the highest volcanic peaks in Mexico; recently extinct volcanoes in California, Oregon, and Washington; and higher summits and smaller active volcanoes in Alaska, are similarly situated with respect to the Pacific Coast. The plateaux and plains east of these ranges form the major portions of both American continents, with minor mountain ranges and less conspicuous highlands near the Atlantic Coast. In the eastern hemisphere the great Eurasian continent has no extensive coastal range corresponding to the western ranges of North and South America. The greatest elevations are in ranges and plateaux trending in a general manner east and west, with many variations in direction, and with minor ranges having a nearly meridional trend. The Himalaya range, with Mt. Everest, 29,002 feet in height, is remote from the sea,

having the peninsula of India to the south and the high plateaux of Central Asia to the north. No dominant range of lofty mountains occurs in Africa, but scattered ranges and mountain groups, the loftiest situated in the region of the great Rift Valley in Eastern Africa. The continental island of Australia has low marginal ranges along the east coast, and disconnected groups of mountains near the other coast lines. The chains of mountainous islands, chiefly volcanic, that extend from Sumatra through the East Indies, the Philippines and Japan to the Kurile and Aleutian Islands, and the chains of volcanic islands in the Southern Pacific are salient features of the visible surface of the solid earth familiar to all, and are available for forming a mental image of the inequalities of the earth's surface above the level of the sea. But only a quarter of the earth's surface is above the sea, and the sea is not level.

Owing to the attraction of the rock mass of the land, which is greater as the coastal regions are more elevated and more ponderous, sea water is drawn up along the coast lines, with a consequent slight depression of the general level in mid-ocean. It has been estimated that the altitude of the surface of the sea off the west coast of South America is 300 or 400 feet higher than it is in the Central Pacific. Moreover, the sea level is somewhat different along the coasts of continents and islands according to the massiveness of the adjacent body of land. However, only the major features of surface variation need to be taken into consideration at this time.

Three-fourths, more exactly 72 per cent, of the earth's surface is covered with water, and its inequalities can only be known from soundings, and consequently only in a very general manner. It may be assumed that the

topography of the ocean's floor differs greatly from that of the land which is exposed to the erosion of rains and streams; that it is characterized by rolling plains, rarely cut by cliffs or escarpments, and that only in proximity to the coasts are there narrow valleys or fjord-like trenches.

From soundings already made, this vast flooded territory is known to be much deeper below the sea's surface than continents are above it. The accompanying map shows the variations in its surface in a very general manner.[1] The greatest depths occur in large depressions or deeps, over 3,000 fathoms, or more than 18,000 feet, deep. There are thirty-two of these deeps in the Pacific Ocean, nineteen in the Atlantic, five in the Indian Ocean, and one that is partly in the Atlantic and partly in the Indian Ocean. Depths of over 5,000 fathoms, or 30,000 feet, have been found in the Challenger and Aldrich deeps in the Pacific Ocean. A depth of 31,614 feet has been sounded near the island Guam, and recently one of 32,113 feet has been recorded just east of Mindanao in the Philippines. This is the greatest depth that has been recorded up to the present time, and when added to the height of Mount Everest, 29,002 feet, assuming that the two measurements have been referred to the same base level, the maximum difference in the inequalities of the earth's surface is 61,115 feet. The average elevation of all continental masses above sea level has been estimated to be 2,411 feet, while the depth of a universal ocean, if the earth's surface were without warping, would be 9,000 feet; consequently, the average depth of the present oceans must be about 12,500 feet.

As to the configuration of the sea bottom, there is a

[1] Murray, Sir J., and Hjort, J. *The Depths of the Ocean*, London, 1912.

strong contrast between that of the Pacific Ocean and that of the Atlantic. The sides of the Pacific Ocean slope much more steeply from the continents and marginal islands than do the sides of the Atlantic. On the west coast of South America there is a remarkable slope from the heights of the Andean Cordilleras to a depth of 2,000 fathoms, and in one place to more than 3,000 fathoms; while in three places very near the coast there are deeps of more than 4,000 fathoms. Other soundings of more than 4,000 fathoms in the Pacific have been taken very near land, off the Aleutian and Kurile Islands, Japan, Philippines, Ladrone, and Pelew Islands; between Solomon Islands and New Pomerania; to the north of New Zealand, and east of the Kermadec and Friendly Islands. The significance of the position of these deeps with respect to neighboring land masses will be noted in another connection. For the present it is only necessary to point out their distribution and to call attention to the relative elevations of different parts of the earth's surface in order to show the bearing of these facts on the question of the homogeneity or heterogeneity of the earth, when considered laterally or in planes parallel to its surface.

Is it likely that portions of the earth's mass possessing differences of elevation amounting to 40,000 and 50,000 feet, and involving volumes of rock millions of tons in weight, would remain in such adjustment for ages near the surface of a spherically homogeneous globe, whirling at such a velocity that with its present consistency it has acquired an equatorial displacement greater than the maximum inequalities of its present surface elevations? In reply it might be answered that the earth's surface does not remain for ages in any fixed position, and that there are abundant evidences that dislocation and warp-

ing is taking place gradually at the present time, and has been much more extensive in comparatively recent geological periods. Indeed, there are those who have believed that continents and oceans have exchanged places with one another repeatedly within geologically historic times. But this idea was combated as early as 1846 by James D. Dana, and also by Studer of Switzerland, who maintained that continental and oceanic areas have retained their separate characters throughout the history of the earth so far as known to us, and that the recorded changes of elevation and depression have not been so extensive as to reverse the relative elevations of the major portions of the earth's surface.[2] This opinion is widely shared by other geologists at the present time. Large areas of the continents have been under the sea for vast periods at different times, and some areas now covered by the sea have been above sea level in times past, but there is no evidence that all of the great deeps have ever been dry land, and there are sufficient reasons for believing that they have for long periods represented depressed portions of the earth's surface.

In 1852, Archdeacon J. H. Pratt investigated the behavior of the pendulum in the region south of the Himalaya Mountains, and concluded that there is a deficiency of gravity in this great mountain mass.[3] Afterwards he propounded the theory of compensation, whereby the maintenance of mountain masses and ocean deeps was referred to differences of density in the underlying parts of the earth; the surfaces of heavier portions sinking and those of lighter parts remaining elevated. Subsequent observations by various investi-

[2] Dana, J. D. Am. Jour. Sci., 7, 1846, 9.
[3] Pratt, J. H. *Figure of the Earth.*

gators have led to conflicting opinions as to the evidence of direct observations on the density of outer portions of the earth. But recent studies by J. F. Hayford and William Bowie within the United States, of O. E. Schiötz along the margins of the continents, and of O. Hecker over the oceans, have established a general relationship between continental and oceanic areas and the density of the underlying earth.[4] There is greater density beneath deep oceans and less beneath the continents. The relationship, however, is by no means simple, and much further study is needed. Moreover, there are serious doubts as to the proper interpretation of observations already made. At present it appears that the Pacific and Atlantic oceans are alike in having a broad belt of heavier matter bordering the continents, then a neutral or lighter zone, within which there is an area of heavier matter. A large central heavy region under the Pacific Ocean surrounds the Hawaiian Islands. The densest locality so far noted is in the Indian Ocean. For the Mediterranean Sea only negative values have been recorded—that is, gravities less than the normal. In a part of the Tonga deep, in the Pacific Ocean, at a depth of about 4,250 fathoms, a very considerable negative value has been found, while on the Tonga plateau at a depth of about 1,350 fathoms, there is a very high density.

For the area of the United States, Hayford and Bowie

[4] Hayford, J. F. Proc. Wash. Acad. Sci., 8, 1906, 25; U. S. Coast and Geod. Survey, Washington, 1909, and 1910; Science, 33, 1911, 199. Hayford, J. F., and Bowie, William. U. S. Coast and Geod. Survey, Spec. Pub., 10, Washington, 1912. Bowie, W. U. S. Coast and Geod. Survey, Spec. Pub. 12, Washington, 1912; Am. Jour. Sci., 33, 1912, 237. Schiötz, O. E. Skrift. Vedensk. Selsk., Christiania, 1908, No. 6. Hecker, O. Veröff, k. Preuss. geodät. Inst. Berlin, 1903, No. 11, 1908, No. 12.

have found from a study of deflections from the vertical that with the exception of certain anomalies, to be noted later, "isostatic compensation departs on an average less than one-tenth from completeness," and that "it is probable that under some areas there is over-compensation as well as under-compensation under others." The continent rises above the sea because of the relatively lighter character of the underlying material. They have suggested that at a depth of about seventy-one miles, 122 kilometers, isostatic compensation may be complete. However, after allowances for topographic relief, there remain anomalies of density which need to be accounted for. Since they are not in accord with surface relief, or with the character of the rock formations at the immediate surface of the earth, G. K. Gilbert has suggested that they are best explained, in part at least, by local differences of density in the material below the zone of complete isostatic compensation postulated by Hayford and Bowie—that is, they may be due to the nucleal structure of the earth, or its heterogeneity. He considers that they may be due also in part to irregularities in the vertical distribution of densities within the lithosphere.[5]

At Washington, D. C., there is an excess of gravity which is equivalent to +.037 dyne, or about 1,230 feet of rock having a density of 2.67; while at Baltimore, Md., about forty miles distant, there is a deficiency equivalent to —.011 dyne, or 360 feet of rock. The greatest anomaly so far observed is at Seattle, Washington, at which place there is a deficiency amounting to —.093 dyne, or about 3,100 feet of rock having the density named; and at Olympia, fifty miles distant, there is

[5] Gilbert, G. K. U. S. Geol. Survey, pp. 85-C, Washington, 1913; also Jour. Geol., 3, 1895, 331.

an excess of gravity of +.023 dyne, equivalent to 1,100 feet of rock; the difference between these two localities being about the same as if their relative altitudes were 4,200 feet, whereas both are at sea level. The difference in gravity between Washington and Baltimore is equivalent to a difference of 0.5 in the density of a body of rock 8,544 feet deep, and that between the gravity at Seattle and that at Olympia is equivalent to a difference of 0.5 in the density of about 20,000 feet of rock.

Differences of gravity of this magnitude at localities so near together must be due to differences in the density of rocks comparatively close to the stations at which the observations were made; that is, within the lithosphere in the neighborhood of the stations rather than at great depths. For the greater depths within the earth at which differences in mass exist, the wider the area of their influence at the earth's surface. Moreover, such local anomalies seem to indicate that the lack of isostatic adjustment of the topographic relief of the surface is due to the effective rigidity of the rocks within which the differences of density exist; a rigidity which is more effective the nearer the surface of the earth; that is, the less the superincumbent load.

In general it may be said that the principle of isostasy obtains for the major features of the earth's surface; the great regions of depression are underlain by denser portions of the planet, and great regions of elevation overlie lighter portions, and it is because there are differences in density in underlying portions of the earth that there are such great differences in elevation of the superficial portions. In other words, lateral heterogeneity of material is clearly indicated.

However, as already said, the relative elevations of neighboring parts of the earth's surface do not remain

unchanged for geological ages. Constant but extremely slow variations are taking place through the erosion of land surfaces by waters and winds, and the deposition of sediments in places where the currents lose their power of transportation. The materials of mountains and plateaux are being moved seaward at rates that depend upon the steepness of slope of the land and the volume of water precipitated, and on other factors. Upon entering deep waters along a coast, heavy material comes to rest near the shore at depths determined by the lower limit of wave action and the stronger currents; lighter material is carried farther out according to the slope of the sea bottom and the strength and volume of transporting currents. The bulk of the sediments derived from land is deposited within short distances of the coast, and forms comparatively narrow borders to continents and islands.

Soundings at sea have shown that sands, gravels, and muds derived from land erosion are found close to land, at depths varying from a few feet to 100 fathoms, which is sometimes called the "mud-line." This is about the edge of continental shelves, like that off the east coast of North America. Beyond the continental shelf and in deeper waters less abundant deposits consist of various kinds of muds and calcareous ooze, derived from pteropods and globigerina, pelagic deposits, which are mixed in various proportions according to location and to some extent the depth.[6]

Calcareous oozes are found chiefly in tropical and subtropical oceans at variable depths, pteropod ooze occurring as low as 2,000 fathoms, globigerina ooze at depths which in the North Atlantic reach 3,500 fathoms.

[6] Murray, Sir J., and Hjort, J. *The Depths of the Ocean,* London, 1912.

The siliceous oozes formed from microscopic tests of diatomaceous and radiolarian organisms, occur chiefly in polar regions and where clayey matter is abundant in the waters. Diatomaceous ooze commonly occurs at depths of from 600 to more than 2,000 fathoms, and in the Northern Pacific is found at 4,000 fathoms. Radiolarian ooze is characteristic of deep waters and is seldom found at less than 2,000 fathoms. It covers the bottom at depths of 4,000 and 5,000 fathoms. This deposit may be considered possibly as a variety of red clay with unusually large proportions of radiolarian remains.

Red clay is the most widespread deposit at the greatest depths, and is found mostly below 2,700 fathoms. It may have been derived from volcanic dust and pumice. Its extremely slow rate of deposition is indicated by the relative abundance of the hard parts of some of the large sea animals, such as sharks' teeth and earbones of whales, some of extinct species. It also contains cosmic spherules and much altered volcanic matter. It also possesses a relatively high content of radioactive matter. In this shifting of material from one part of the earth's surface to another, the maximum rate of removal takes place in high mountains, the maximum deposition along coasts and on continental shelves, and the smallest amount of marine deposition occurs in the ocean deeps.

The lithosphere is so much of the outer portion of the earth as is composed of rock material having the physical properties of the rocks exposed to view at its surface. From the structure of the rock masses forming the upper part of the lithosphere, and from the nature of the rocks themselves we obtain some knowledge of the physical characteristics of the outer portion of the earth. The structure of the lithosphere, so far as known,

is so highly complex that only its salient features can be noted at this time. Moreover, it is to be remarked that only a quarter of the surface of the lithosphere is above the sea, and of this only a portion has been closely investigated. However, the recurrence of similar rock bodies with similar structural relationships in widely remote localities warrants the assumption that our knowledge of the essential characteristics of so much of the lithosphere as is within reach of our observation is reasonably complete, although we are ignorant of the constitution of those portions that are beneath the oceanic deeps, but may infer the possible character of marginal portions from that of neighboring land masses. The rocks exposed at the earth's surface differ widely from one another over large areas, both as to composition and structure, but no attempt will be made to describe their distribution, it being sufficient for the purpose of this discussion to summarize their characteristics and relations to one another, noting certain occurrences by way of illustration.

Great areas of the continents are covered by sedimentary deposits, the composition, succession and extent of which show the constitution of these portions of the lithosphere, and indicate the movements that have taken place in them in times more or less remote. In the Appalachian region there are sandstones, shales, and limestones representing an accumulation of submarine deposits variously estimated at from 30,000 to 40,000 feet in the thickest parts, which thin out rapidly westward, and indicate that during their deposition the sea gradually became deeper for long periods of time, and then shallower, and that these changes recurred periodically.[7] Coarse conglomerates of sand and gravel, and

[7] Keith, Arthur. U. S. Geol. Survey, folio 147, Washington, 1907.

muds that became shales, formed along the eastern border of the region in early Cambrian times. As the water became deeper the sediments became finer and more calcareous, and 4,000 feet of dolomitic limestone were deposited. This was followed by shallower waters and the sedimentation of coarser material, forming sandstones that subsequently were exposed above sea level. This happened at the end of the Silurian period, when the Green Mountains began to appear as permanent elevations, and a great arching of the rocks took place in the region of Cincinnati, from the latitude of Lake Erie to that of Tennessee.

The unequal thickness of the deposits in different parts of the regions covered by them shows that the surface on which they settled warped during the process of sedimentation, whatever may have been the chief cause for the changes in sea level. Beneath the thicker deposits the earth's surface must have been depressed with respect to those portions that are beneath thinner deposits.

After the exposed land area in the Appalachian region was eroded nearly to sea level, muds forming black shales were deposited, and subsequently alternating layers of shales, limestones, and sandstones were formed, showing that there were slight oscillations of sea level in this region during Devonian times. A long period of deepening seas permitted the deposition of massive limestones. Then the waters became shallower again and portions of the limestone became dry land or swamps, and extensive coal-bearing shales with layers of sandstone were formed. At the end of this period, the Carboniferous, the greater part of the Appalachian region became dry land, and mountain-making movements were inaugurated. In the manner just described the 30,000

or 40,000 feet of limestones, sandstones, and shales were laid down in Paleozoic times. During this great period no extrusive volcanic eruptions took place within the Appalachian region, although a large body of granite, the Whiteside, appears to have been intruded within underlying rocks in post-Cambrian times, possibly in the Carboniferous period. Oscillations of the earth's surface and of sea level were the principal dynamic events accompanying the sedimentation that has been described as taking place in this part of the earth. To the northeast of the Appalachian region, in the Green Mountains, and especially in Maine and eastern Massachusetts, volcanic activity began in Cambrian times, and recurred again and again throughout the Paleozoic era.

A very similar succession of deposits was laid down in the region of the Rocky Mountains, except that the total amount of sedimentation was much less, and the periods during which the region was above the sea were much longer than in the eastern region; so that some great formations, which are well developed elsewhere, are absent, or are represented by comparatively thin strata. Moreover, sedimentation continued with little or no surface warping into Mesozoic times, when deposits were laid down almost conformably upon Carboniferous limestones, which were not covered with coal-bearing strata; showing that in Mesozoic times the sea continued to cover this region, although the greater part of the Appalachian was above water. In the western region, toward the end of the Mesozoic period, sedimentary strata were upturned and profoundly faulted, and vigorous volcanic activity broke forth, continuing in some districts throughout Tertiary times, and farther west almost to the present day.

In northern Russia, where Cambrian strata have remained in nearly horizontal position almost undisturbed since they were deposited, Cambrian muds still become sticky when wet by rain, and are not shales. In central Russia some sands beneath Carboniferous limestone are as loose and incoherent as any on a modern sea beach. Age alone does not produce induration or metamorphism of such material. It is the weight of superincumbent strata and pressure from other sources, with possibly some rise of temperature and cementation by interstitial solutions, that bring about the induration of mud to shale, the crystallization of some limestones, and the solidification of some sandstones. However, there are sediments that have been covered by 20,000 feet of strata, in Wales and elsewhere, which have been brought to the surface by dislocation and erosion, that do not exhibit any considerable alteration or metamorphism, showing that at such depths they may not experience any considerable rise in temperature or other metamorphosing agency. On the other hand, in southern Norway, nearly horizontal Paleozoic strata have become highly indurated dense rocks, considerably metamorphosed, without evidence of their having been buried under any great thickness of overlying strata. The highly metamorphosed condition of stratified rocks in the Swiss Alps, and in parts of the Appalachian Mountains, accompanies, and undoubtedly results from, the complex plication, shearing, and compression of the rocks of these regions during intense local warping and displacement.

In some regions volcanic tuffs and breccias have mingled with sediments, and form parts of the stratified series; and surface lavas have flowed over sediments and have been covered by later sedimentary deposits;

the whole making a complex series of formations, such as occur in the Lake Superior region.[8] Here the oldest known formation consists of highly metamorphosed sediments and surface volcanic rocks, greenstone-schists and greenstones, with iron-bearing cherts, traversed by igneous intrusions of various kinds, the Keewatin formation. After this accumulation had experienced great changes through metamorphism it was exposed at the earth's surface by erosion, and was overlaid by another series of sediments and volcanic lavas, known as the Huronian. Still later, there was deposited a great series of sediments and volcanic rocks, mostly lava flows which vary in thickness from two to 100 feet, some of which have been traced for ten or thirty miles, and some groups of flows for 150 miles. This formation, the Keweenawan, extends over an area at least 400 miles in diameter, and occupies a great depression, or synclinorium, exhibiting repeated warpings which appear to have been contemporaneous with the accumulation of the strata, for the lower formations are more plicated and metamorphosed than the upper ones. This complex series of stratified and igneous rocks is much older than the Paleozoic series previously described, and is overlaid by it in numerous places.

Similar and even more complex formations underlie Paleozoic sandstones in many parts of the earth. Highly crystallized rocks, schists, gneisses, quartzites, and marbles, with large bodies of granite, gabbro, and other igneous rocks, besides veins and dikes of coarse-grained pegmatites and fine-grained porphyries, form the basement on which all known stratified rocks have been laid down. They represent still older formations;

[8] Van Hise, C. R., and Leith, C. K. U. S. Geol. Survey, Bull. 360, Washington, 1909.

Fig. 37. Folded limestone and dolomite, Lehigh Co., Pa.

T. N. Dale, U. S. Geol. Surv.

in part, sedimentary deposits, which have been under great pressure and have experienced profound plication and shearing, and possibly high heating; in part, they are igneous rocks that have been subjected to similar stresses, and some that have experienced little or no alteration since they were intruded into the already highly metamorphosed rocks. These complexes were at one time considered to be remnants of an original crust of a once liquid globe; at another, the early sediments from a heated ocean. They do not differ from highly metamorphosed sediments and igneous rocks of Paleozoic, and even of more recent age, which have been changed through local conditions especially favorable to recrystallization and shearing. They are pre-Cambrian sediments and igneous rocks formed in eras when the long line of ancestors of the Cambrian fauna were developing from their earlier progenitors.

It is probable that similar highly metamorphosed rocks underlie the Paleozoic and more recent strata in all parts of the earth, unless there are portions of the lithosphere that have escaped the stresses which produced plication and shearing through long periods before Cambrian time, as there are regions that have escaped such stresses for millions of years since that time. Some series of pre-Cambrian stratified rocks have escaped shearing and profound metamorphism, and show what may be found, perhaps to a greater extent in some unexplored region, or may exist beneath a covering of more recent formations. Such are the shales, limestones, and sandstones of the Belt formation in Montana, which have a thickness of 12,000 feet.[9]

Vast accumulations of sediments must have been

[9] Walcott, C. D. Bull. Geol. Soc. Am., 10, 1899.

derived from immense land masses which formed mountain ranges of continental dimensions. The location of these ancient lands is one of the unsolved problems of geology that has opened wide the doors for speculation. The great northern protaxis of crystalline rocks in Canada may be the basal remains of a pre-Cambrian continent, whose erosion supplied much of the material for the Paleozoic deposits to the south and west, but the narrow belt of pre-Cambrian crystalline rocks along the eastern border of the Appalachian region, if it represents the eroded surface of the parent land mass of these sediments, must be only its western edge; the land itself having existed to the east, where the continental shelf is now situated.

The Appalachian Mountains are the eroded remains of a land mass whose present summits range from 2,000 to 6,700 feet above sea level. Before erosion the mass may have stood higher; the lowest Cambrian sediments were once 30,000 feet lower than sea level. The pre-Cambrian continent to the east was at one time high enough and massive enough to supply the bulk of the 30,000 or 40,000 feet of sediments deposited beyond its western margin. In its place the mud-covered continental shelf lies 10 to 100 fathoms beneath the sea. Apparently there has been a great warping of the earth's surface in this region, and if the character of the Paleozoic sediments indicates gradual and periodic depressions and elevations, or arrested phases of depression, these may have been counterbalanced by a gradual elevation of the continent which was being eroded. That is, it is possible that at no time was the continental mass above sea level large enough to yield all the sediments that may have been derived from the continent in the course of ages; the continent may have

FIG. 38. PLICATED LIMESTONE, SILVER PEAK, NEV.

C. D. Walcott, U. S. Geol. Surv.

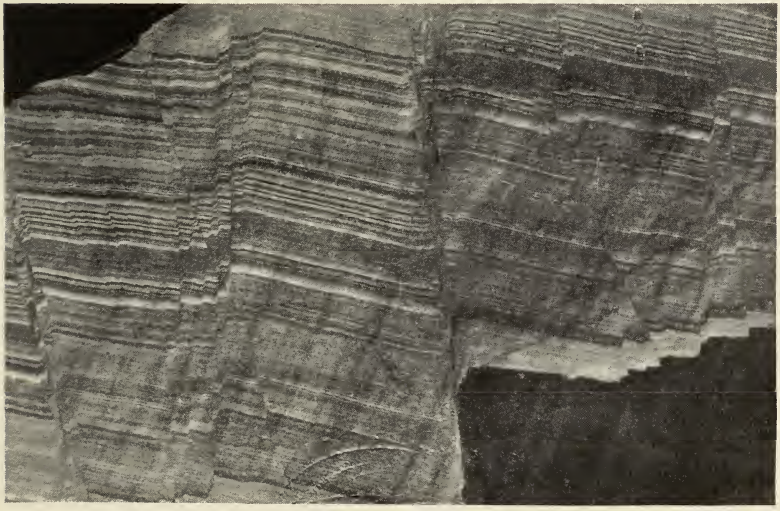

FIG. 39. FAULTED SANDSTONE, SOUTH DAKOTA

U. S. Nat. Mus.

risen gradually as it was being eroded, not necessarily at a uniform rate, but periodically.

The question whether the elevation of a land mass with respect to sea level, or with reference to other land masses, is actually a movement away from the center of the earth, or merely an apparent elevation due to the depression of surrounding bases of comparison, is likely to remain an open one for some time, so far as demonstration goes; for while it is probable that depression of the sea bottom over large areas is a preponderant cause of change of sea level, possibly producing the elevation of sea beaches and of cliffs in some instances, and the apparent rise of land from the sea; nevertheless, the warping of the earth's surface and the known rigidity of the strongest rock masses render it equally probable that some small amount of elevation in some instances is the result of vertical displacement away from the earth's center.

What were the uppermost portions of these ancient continental masses? No doubt, they were different from the eroded foundations that are now exposed in places, which must have been deeply buried beneath overlying sediments that carried the fossils of pre-Cambrian fauna. These ancient sediments, themselves the redistributed fractions of previous sedimentary deposits, have been redeposited as Paleozoic formations, in places to be again transported and transformed into more recently stratified rocks.

Warping of the earth's surface is indicated not only by the varying thickness of stratified deposits, but also by the arching of strata, both upward in anticlines and downward in synclines. In places the arching has gone so far as to produce folds and plications of sedimentary beds. These have been highly developed in parts of the

Appalachian Mountains and in the Swiss Alps. However, there are distinctions between broad warping of the earth's surface, together with that of the underlying lithosphere, and the folding and crumpling of strata composing it, although there may be a genetic relation between them.

The simple bending of a set of parallel layers of any flexible substance will compress those on the concave side of the arch, and stretch those on the convex. The layers subjected to compression must either thicken or buckle, that is, crumple up. Those subjected to tensile stress must either become thinner, or rupture across the layers. Rock strata may bend downward because of gravitation, or warp in consequence of lateral pressure which takes place approximately tangential to the surface of the earth. The behavior of different substances having different consistencies when subject to the same compressive stress is familiar to all, and has been well illustrated in experiments by Bailey Willis and others, and is shown by the structure of crumpled rocks in regions of schists and distorted shales. Similar multiple folding also occurs on a large scale in less flexible rocks, as limestones (Figs. 37 and 38). The bending of material like rocks, composed of crystallized minerals, may be expected to be accompanied by cracking, and this is commonly the case, although under some conditions the ruptures may become healed by recrystallization or by molecular adhesion under great pressure. When near the surface of the earth, rupture usually results in cracking accompanied by dislocation along the plane of fracture, which, when considerable, is called faulting (Fig. 39).

The rupturing of rock masses, the position of the planes of fracture, and the displacement of the fractured

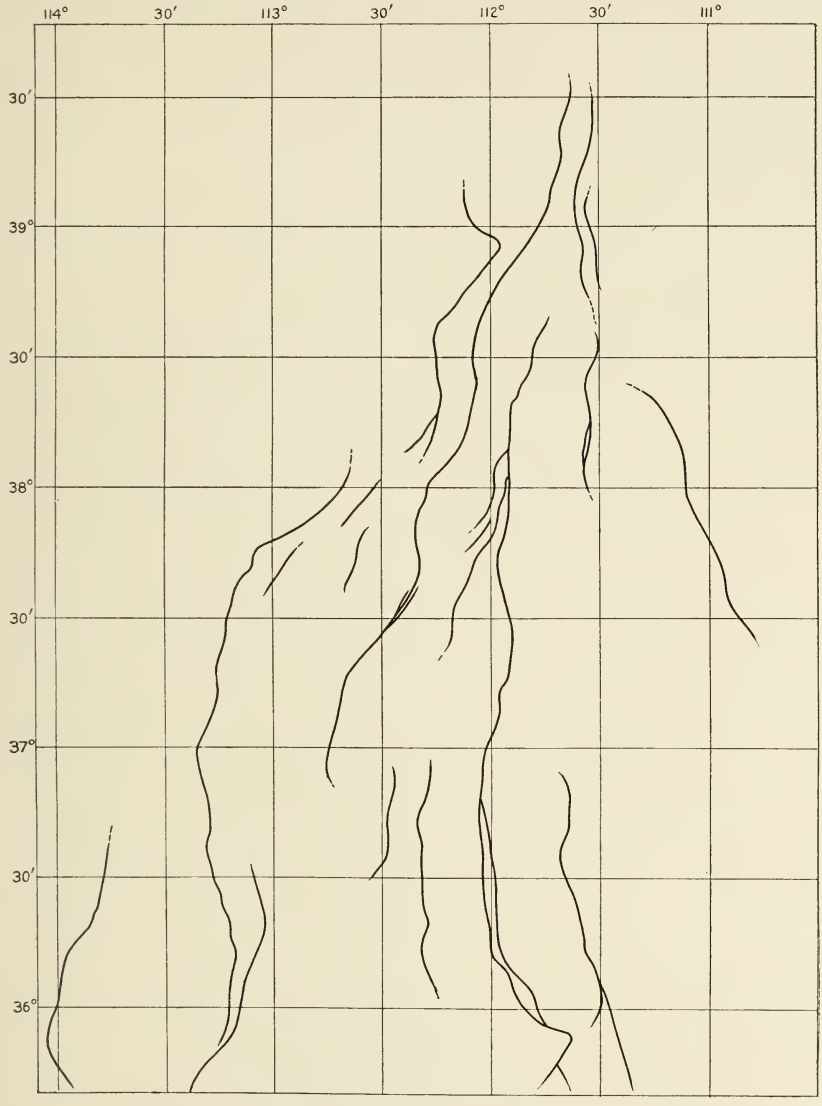

FIG. 40. SYSTEM OF FAULTS IN SOUTHEASTERN UTAH

C. E. Dutton

parts during the warping of the lithosphere, are matters of first importance in a discussion of the intrusion of molten lavas, but in this place it is only necessary to notice the fact of the occurrence of fractures, and their relation to the major movements within the lithosphere; that is, the rôle of faults, and the position of fault planes with respect to warping and folding. Since folding and faulting are only different modes of displacement due to a shearing stress, the first produced by a gradual yielding of a substance within the limits of its cohesion; the second resulting from a yielding by rupture, that is, beyond the limits of cohesion of the material sheared; the folding of rocks may end in rupture and displacement by faulting, or a mass of rock may be folded in one place and fractured in another, where the stresses may have been greater or the substance less pliant. A rock-fold may pass gradually into a fault in which the displacement increases the farther the distance from the folded portion. It also happens that the shearing of a very thick body of rock may result in folding in the lower portion and faulting higher up, or in folding in the upper portion and faulting below. It follows from this, that the warping of the lithosphere may result in bendings that pass into faults laterally, or that end in faulting after only a small amount of folding or flexure has taken place.

As pointed out by G. K. Gilbert in 1875, there are movements of the lithosphere that result in fractured blocks of great size, which exhibit slight flexure but profound faulting which has displaced the rocks for a depth of thousands of feet, and has produced systems of nearly parallel mountain ranges, as in the Great Basin of Utah and Nevada, the ranges representing tilted

blocks dipping at relatively low angles.[10] In the High Plateaux of Utah a system of nearly meridional faults and flexures traverses the country south of the great Wasatch fault, and illustrates the character of the structure of the Great Basin region (Fig. 40), in which the major fault planes trend with the ranges approximately north and south.[11] Transverse faults cross these ranges dividing them into blocks, some of which have sunk thousands of feet lower than others. In the vicinity of these sunken blocks, great eruptions of rhyolitic lava have taken place, in some instances, forming mountain groups seventy and eighty miles long, the lava being 3,000 and 6,000 feet thick. In the Yellowstone Park[12] region, faults of 15,000 feet and more cut the sedimentary strata and underlying schists, as well as overlying volcanic tuffs and breccias, in such a manner as to show that a synclinal movement in the lithosphere was accompanied by repeated displacements and faultings and by repeated intrusions of igneous material. The whole region of the Yellowstone plateaux, the vast lava plains of Idaho, and the territory of the Great Basin are areas of depression with respect to surrounding mountainous regions, and are characterized by faulted blocks in which folding is a very subordinate feature. Other great regions of slightly warped blocks, some of vast dimensions, occur in European Russia, in Northern Siberia between the Lena and the Yenisei Rivers, in the peninsula of India, the greater part of Africa and the middle portions of North and South America.[13]

[10] Gilbert, G. K. U. S. Geol. Survey, Expl. Survey W. 100th Mer., Wheeler Rep., III, 1875, 62.

[11] Dutton, C. E. U. S. Geol. Geogr. Survey, Rocky Mountain Region, High Plateaux of Utah, Washington, 1880, 25.

[12] Iddings, J. P. Jour. Geol., 12, 1904, 98.

[13] Suess, E. *The Face of the Earth*, vol. 2, 1906, 254.

FIG. 41. OVERTHRUST FAULT, NEAR HOUSTON, I. T.

J. A. Taff, U. S. Geol. Surv.

In East Africa the Great Rift Valley occurs on lines of profound faulting which has taken place almost meridionally, and extends northward with some interruption into Syria through the valley of the Dead Sea. Long blocks of the lithosphere have sunk between adjacent ones, often in a step-like manner, because of nearly parallel fractures; the resulting troughs being marked by great lakes and drainage channels, and by eruptions of volcanic lavas. Profound fractures may traverse mountain ranges, as already remarked, dislocating the lithosphere across axes of folding, and the sunken blocks may be submerged in the ocean, so that the coast line may cross the end of a ruptured and depressed range of mountains, as in parts of the Atlantic Coast of Europe; or the sea coast may be the edge of great, faulted blocks, or may cross the surface of tilted ones, as on either side of Central Africa and the Indian peninsula, as pointed out by Suess.

Highly complex folding, as already said, commonly results from compression parallel to the planes of stratification or nearly tangential to the surface of the earth; is in places accompanied by overthrust-faulting, a simple illustration of which is shown in Figure 41; and as Gilbert has remarked, appears to be superficial as compared with the more profound block-faulting.[14] The Appalachian range consists of much-folded strata which are in part bent to such an extent that they have cracked along the crest of a fold and the upper portion has been thrust over the lower for long distances, in some places for 300 miles; the fracture crossing many thousand feet of strata, the amount of displacement being ten or

[14] Gilbert, G. K. U. S. Geol. Geogr. Expl. Survey, W. 100th Mer., Wheeler Rep., III, 1875, 62.

fifteen miles, 50,000 or 80,000 feet. In western Scotland overthrust-faulting has superimposed the oldest gneisses and schists on Cambrian strata, and similar overthrusting on a large scale has taken place in Scandinavia. The most remarkable example of complex folding and overthrusting is to be found in the Swiss Alps. A section through the Tödi-Windgällen group, drawn by A. Heim,[15] is shown in Fig. 42. Such highly compressed masses of folded and overthrust rocks seldom contain bodies of igneous rocks that were intruded or erupted during the process of plication.

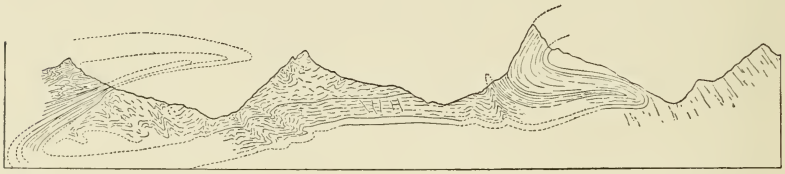

Fig. 42. Overturned strata, Tödi-Windgällen, Switzerland

A. Heim

However, between the extremes of greatly compressed or crumpled rock masses and very slightly bent or warped ones there are all gradations, and ranges of more or less folded rocks occur in many parts of the earth, commonly in subparallel systems, the major folds following each other like waves of the sea. In the Appalachian region the sedimentary strata in the western part, the Cumberland plateau, are generally flat and unaltered; passing eastward, they are bent into parallel folds, in places steeply tilted, broken by parallel faults, and to some extent altered into slates. Still farther east, in the mountain district, they have been more and more

[15] Heim, A. *Mechanismus der Gebirgsbildung,* Basel, 1878, Plate IV, Profile V.

metamorphosed, with slaty cleavage and fractures dipping for the most part about 60° southeastward.

In some regions the fracturing that accompanies the dominant folding forms a system of faults having the same trend as the principal folds, usually that of the mountain ranges; and along some of them volcanic lavas have been erupted. Such are the great Cordilleran systems on the Pacific Coast of North and South America, where the strata are somewhat plicated in long meridional folds, in part overturned or overthrust toward the east, away from the ocean. In this vast territory, dislocation of the lithosphere at various periods was accompanied by volcanic activity. Recent dislocations and faulting in the region of San Francisco show that the movement is appreciable at the present time in this locality; and earthquakes and active volcanoes in many places to the north and south, from Alaska to Patagonia, show that the whole region is in a condition of unstable equilibrium.

The parallelism of the Cordilleras and the sea coast, the steep descent from their summits to ocean deeps, which are also parallel to the coast, and the instability of the lithosphere in this region suggest an intimate relation between them. Many of the deep troughs of the Pacific are situated near the coast lines of chains of islands, such as those off the coast of the Aleutian and Kurile Islands, Japan, and the Philippines, and others farther south. These deep troughs represent profound warpings of the lithosphere, as suggested by Supan, the chains of islands being crests of earth waves in some instances, although in others they are volcanic ranges piled up on intermediate lines between crests and troughs of the folds, according to Suess. The curved chains of islands from the Aleutian to the Dutch

Indies, in large part volcanic, also consist of folded strata crumpled and overthrust toward the sea coast. The deep troughs may be geosynclines produced by step-faulting, as suggested by von Richthofen; and, as James Geikie has remarked, the volcanic islands situated in ranges and groups along the margin of the Pacific, and across its southern portion, probably have resulted from tensional stresses caused by the sagging of the sea floor, which is on an average deeper in the western than in the eastern part of the Pacific Ocean.[16]

Sedimentation on the bottom of these deep troughs is very meager and takes place very slowly, as already noted. Where the deeps are off the shores of islands little material is supplied by erosion of the land masses, while off the western coast of the American continents the proximity of the continental divides and the great depth of the ocean floor prevent any considerable amount of material from reaching the deeps in this part of the ocean. Whether deeps have ever occurred in places where sedimentation was sufficient to fill them more or less completely is a question whose answer may depend on the definition of a deep, for the depression of the lithosphere that permitted the deposition of 30,000 or 40,000 feet of strata in the Appalachian region was a curvature of sufficient depth to have been a deep, if it had not been filled with sediments. However, it has been shown that sedimentation took place at nearly equal rate with depression, and at no time probably was there any great depth of sea—that is, no deep, in this region If sedimentation had not taken place, would this depression have existed at one time as an empty deep? The

[16] Richthofen, F. von. *Fuhrer fur Forschungsreisenden* (1886), 1901, 594. Geikie, James, *Mountains,* Edinburgh, 1913, 231.

remarks of J. D. Dana in connection with Appalachian sedimentation furnish a proper answer to this question.[17] He considered the great depth of sedimentation in this region to be a consequence of the depression, not a cause for it; for, as he remarked, it was not reasonable to assume that the accumulation of sediments along a coast would necessitate a depression of the underlying lithosphere when much denser masses of rock in mountain ranges found solid support. We may conclude, then, that warping of the lithosphere permits erosion and denudation of exposed masses and consequent sedimentation; that it takes place independently of them, and when the warped surfaces remain beneath sea level beyond the reach of sedimentation they maintain their relative positions unchanged, except when subsequently displaced by further warping or faulting. Unfilled troughs on a small scale, within continental areas, may possibly be found in Death Valley, California, and in the valley of the Dead Sea, in Syria.

The movements of the lithosphere that have been briefly noted are irregularly periodic. The warping that has been recorded in any series of strata has never proceeded at a uniform rate. There appear to have been periods of gradual subsidence, followed by the cessation of movement, or by relative elevation; then further periods of depression, and great eras of quiet, or of gradual relative elevation. There are regions of wide extent which appear to have escaped considerable tangential compression or folding for vast periods of time, but which subsequently yielded to compressive stresses; at first gradually bending, then rupturing and faulting with great displacement of material; in some

[17] Dana, J. D. Am. Jour. Sci., 5, 1873, 347.

instances accompanied by violent volcanic activity that has continued for long periods.

Such changes from comparative quiet to profound movement and displacement plainly indicate the yielding of a resistant body to an excessive stress; a body that may yield gradually to a long-applied stress somewhat above its limit of elasticity, and ruptures when the stress exceeds the limit of its cohesion. The recorded movements of the lithosphere show that it behaves as a solid elastic body, capable of plication and warping within the limits of its cohesion. They also show that at irregular intervals this limit is passed, and that it is fractured into blocks which readjust themselves according to the nature of the stresses acting on them. This process of yielding and readjustment has taken place from the earliest period of recorded movements, and is still active.

From the foregoing considerations we may conclude that the earth is a heterogeneous globe, denser in some places than in others; that it is continually under stresses that tend to warp its outer portion; that the resultant warping is very different in amount and in character in different parts of the lithosphere, and is accompanied by the eruption of volcanic lavas in some instances, and not in others. What then is the actual physical character of the lithosphere? What are the stresses acting within it? And why do lavas break through it in some places and not in others?

CHAPTER IV

PETROLOGY OF THE EARTH

Molten volcanic lavas solidify into rocks, they reach the earth's surface through rocks. In fact, all of the solid portion of the earth of which we have any knowledge is rock; in places incoherent it is true, but, nevertheless, rock material. It would seem to be self-evident, then, that a discussion of volcanism should involve a consideration of the essential characteristics of rocks, as well as of the molten liquids or lavas from which all igneous rocks are formed. However, this has not always happened; theories of volcanism have been evolved in some instances with little or no regard to the rocks and lavas involved.

In some cases the assumptions made as to the physical characteristics of rocks and lavas have been seriously at fault, and the resulting hypotheses proportionately misleading. This has been due partly to imperfect knowledge of rocks and molten magmas, either in general, or on the part of the individual attempting to explain volcanic phenomena. Geologists are not necessarily petrologists, and some theories of volcanism have been enunciated by writers who are not geologists, much less special students in that branch of geology that deals chiefly with the rocks themselves.

The special study of rocks and magmas is a comparatively recent one, and much remains to be learned regarding those of their characteristics that are fundamental to the solution of the problem of volcanism.

However, enough has been established to materially advance the status of the problem, and it is desirable to call attention to those characters that appear to have been established, and to point out those that remain in doubt, or are completely unknown at the present time.

It should be said, by way of introduction, that there are wide differences of opinion among petrologists as to the application of certain physical principles to the discussion of the behavior, or the condition, of rocks and magmas at depths within the earth beyond the limits of our observation; and that in some instances it is the assumption regarding the abstract principle that is at fault; in others, it is the application that is misdirected; in still other cases, it seems to be the failure to apply any principle at all that is to be criticised. The chief difficulty, however, is the incomplete state of our knowledge of the behavior and condition of mineral substances at high temperatures and pressures, and the uncertainty as to what temperatures obtain in rocks and magmas at considerable depths within the earth.

Investigations are being carried on in the Geophysical Laboratory of the Carnegie Institution of Washington and elsewhere which are advancing our knowledge of the behavior of rock materials at high temperatures and under considerable pressures, and it is to be expected that certain elemental principles will be established which will extend our insight into the probable condition of rock material deep within the earth. But it must be remembered that the physico-chemical problems involved are highly complex, and that attempts to calculate quantitatively definite limits to chemical reactions or physical behaviors, when some of the factors involved are unknown, or are ignored, are more than misleading.

Toward such attempts at quantitative exactness in the

present state of our knowledge of the physics and chemistry of rocks and magmas, it is advisable to maintain the attitude of Immanuel Kant toward a nebular hypothesis, namely, that "geometrical precision and mathematical infallibility cannot be demanded of a treatise of this description," and that the most that can be expected of it is, that it should be "founded on analogies and agreements developed according to the rules of credibility, and in a logical manner."

What, it may be asked, are the essential characteristics of the rocks that form the known portions of the earth? and How far below the surface may similarly constituted matter extend? That is, How deep may the lithosphere extend? and What may be the character of the planet beneath it?

Rocks consist in the great majority of instances of crystallized minerals closely adhering together, often interlocking. In many kinds of solidified lavas amorphous glass is a matrix, more or less abundant, through which crystallized minerals are scattered. In some rocks, composed originally of incoherent fragments of crystals, the particles have been cemented together by crystallized minerals, rarely by amorphous mineral matter. Consequently, the characteristics of rocks are the collective characteristics of the crystals composing them. The mass, or weight, of a rock is the sum of the masses of the aggregated crystals in a given volume. The strength of a rock, its resistance toward compression or shearing or crushing, is the resultant of the separate resistances of the individual crystals of which it is constructed. These resistances in the case of most rocks differ considerably among themselves, not only because of the diversity of minerals present, but also because of

the diverse behavior of certain crystallized minerals in different directions within each crystal.

The fusibility of a rock is somewhat more complex, for it depends on the fusibility of the most fusible mineral component, and the ability of its liquid to dissolve the less fusible minerals present. It is a matter of fusibility and solution, and involves the amounts of liquid and gaseous components that may be present, which materially modify the solubility of the whole system. There can not be a definite melting point for an ordinary rock, or a definite limit of elasticity or of cohesion. The complex system must yield at successive points where the resistance is greater and greater.

The minerals, quartz, feldspar, and mica, that are the chief components of many rocks, behave very differently toward shearing stresses. Their resistance toward molecular displacement, that is, their rigidity, or hardness, differs considerably; quartz and feldspar being more than twice as hard as mica. Quartz crystals are brittle and fracture in any direction like glass. Feldspars are comparatively tough, but separate, when broken, along definite planes in several crystallographic directions; while mica separates readily into thin, flexible, elastic plates. Calcite crystals, which constitute limestones, are no harder than mica, cleave in three directions with equal ease, and may be sheared without fracture in three other planes by the gliding or partial rotation of the crystal molecules. Other common rock minerals, hornblende and pyroxene, cleave readily into prismatic fragments, and have about the same rigidity as feldspar.

The resistance of rocks composed of such crystals may be imagined easily. Long, thin slabs of limestone or marble, supported at their ends, bend under their own

weight in the course of time; partly through molecular readjustment within the calcite crystals, partly through minute fractures along the crystal cleavage planes. Rocks composed largely of mica when under considerable stress yield through the bending and crumpling of the mica plates; and if the mica crystals are nearly parallel to one another the rock splits readily parallel to the cleavage planes of the mica, as in mica-schists and in other rocks composed largely of micaceous minerals. Rocks made up of quartz, feldspar, and mica under great stress yield through the crumpling and slipping of the mica plates, the crushing of the brittle quartz crystals, and lastly through the cracking of the more resistant crystals of feldspar. Rocks composed almost wholly of feldspar and pyroxenes are among the most resistant toward shearing stresses. And so it happens that rocks behave very differently under like stresses, and the amount of stress required to shear or fracture different kinds of rocks varies greatly with the mineral composition of the rock, and with the direction in which the stresses act. Take, for example, clay shales, or indurated muds, micaceous schists, crystalline limestones, compact quartzites, granites, gabbros, and pyroxene rock.

All rock minerals are elastic, more or less rigid substances whose limits of elasticity have been determined in some instances with great accuracy. But such constants can not be applied directly to the determination of the limits of elasticity of coherent rocks, because of the complexities of mineral composition and the diverse arrangements of the individual crystals. Direct determinations have been made on the rocks themselves, both to determine the coefficients of elasticity, and the limits of cohesion or crushing strength. However, most rocks

have been subjected within the earth to excessive stresses that have strained and fractured them to a greater or less extent, so that they are traversed by flaws or cracks which lower their power of resistance below what it should be theoretically. Most tests of the crushing strength of rocks have been made on cubical blocks, compressed from opposite sides without support on the remaining ones, a condition of stress not found within the lithosphere, where rock masses are held in place by adjacent bodies of almost equally resistant rocks; it may be more, it may be less resistant.

Two elements of the problem as to the strength of rocks suggest themselves: one is the coefficient of compressibility possessed by mineral crystals, and consequently by rocks, together with the limit of their resistance to molecular displacement under isostatic conditions; the other is the coefficient of rigidity of rocks and the limit of their resistance toward shearing, or displacement in any direction. If the stresses acting on all sides of a rigid body are equal, the body will remain motionless within any system of which it is a part, and will be subjected only to isostatic compression. If, however, the stresses are not equal on all sides, the body will move toward the direction in which the resultant stress is least. If the whole system is liquid, the phenomenon is that of flow. It is the same in a plastic system when sufficiently stressed. Rocks under stresses exceeding the limit of elasticity of their constituent minerals move in like manner; but their constituents being diverse, both in kind and in molecular behavior, the flow is not that of a homogeneous fluid, but of a heterogeneous one. Different parts move with different ease and in diverse manners, so that differential flow ensues, some parts moving faster than others.

The structure of rocks, that is, the arrangement of the mineral crystals, is such in many instances that the interlocking of the more rigid kinds holds the mass together until their limit of elasticity, or of cohesion, is reached before the rock as a whole is sheared, or fractured. Similarly an assemblage of rock bodies, either of stratified limestones, sandstones, and shales, or of interpenetrating igneous masses, may behave to a certain extent as a unit whose strength depends upon that of the dominant members, which may sustain the stress after it has passed the limit of the weaker but subordinate members of the system.

The effect of isostatic pressure is to compress any system, to force closer together the particles of any body, or the molecules of any substance, to increase its density, to reduce the mobility of anything capable of molecular movement by increasing molecular friction or viscosity. The extent to which pressure effects changes in the volume, density, and viscosity of mineral crystals is extremely small, and very little is known as to its molecular effect in the case of the rock minerals.

The adhesion of crystals that are in molecular contact determines the strength of crystalline rocks in which crystals have formed side by side, and when fracturing and displacement occur under sufficient pressure to maintain molecular contact between the fractured parts an equally coherent rock is produced. It follows from this that rocks within the lithosphere, when subjected to shearing stress above their limits of elasticity, may gradually flow and at all times be coherent rocks. Investigations of the compressibility of rocks by F. D. Adams and E. G. Coker have shown that they are somewhat more compressible than cast iron, ranging from

nearly as resistant, in the case of the Sudbury diabase, to about half as resistant, in some granites.

Substance	*Modulus of cubic compressibility D*	
Wrought iron	21,300,000	pounds per square inch
Cast iron	10,000,000	
Marble, various	8,303,000	Average, 5,855,000
	5,341,000	
Granite, various	4,792,000	Average, 4,399,000
	3,940,000	
Nephelite-syenite	6,237,500	
Essexite, Mt. Johnson	6,750,000	Average, 8,825,000
Anorthosite	8,368,000	
Gabbro	9,555,000	
Sudbury diabase	10,626,500	
Plate glass	6,448,000	Average for igneous rocks, 6,353,500

The compressibility of the lithosphere if composed of equal parts of granite and gabbro would be about the same as that of plate glass.[1]

The crushing strength of limestone when tested in the form of cubical blocks has been found to be from 11,000 to 25,000 pounds per square inch. When compressed within a copper cylinder it withstands a pressure of 35,000 pounds before deformation of the cylinder takes place. By increasing the strength of the cylinder a pressure of 296,725 pounds per square inch has been applied, which is equivalent to rock pressure at a depth within the earth of forty-six miles. The resultant rock is as coherent as before deformation, although there had been gliding, fracturing, and readjustment of the calcite crystals. This took place under such pressure that molecular contact was maintained throughout the deformation. The marble acquired a schistose structure. The calcite crystals retained their normal physical properties.

[1] Adams, F. D., and Coker, E. G. Carnegie Institution of Washington, Publ. No. 46, 1906, 26.

Granite in cubical blocks crushes under a pressure of from 7,000 to 22,000 pounds per square inch, but when compressed in a copper cylinder withstands deformation up to a pressure of 50,000 pounds, when in one instance the end of the granite cylinder was sheared. From these experiments it appears that under isostatic pressure, at atmospheric temperatures, crystals of rock minerals retain their physical properties under pressures of 300,000 pounds per square inch, or 20,000 atmospheres, equivalent to a depth of forty-six miles in the lithosphere. Granite, pierced by two holes, 0.05 inch in diameter, when pressed within a nickel-steel cylinder under a weight of one hundred tons per square inch, resisted fracture or shearing for two and one-half months at ordinary temperatures, only a little powder being produced at the extremity of one of the holes. This pressure corresponds to that estimated to exist at a depth of thirty-one miles within the lithosphere. Similar granite with holes in it remained unchanged under a pressure of about fifty tons, or 96,000 pounds, per square inch for seventy hours at a temperature of 550° C., the pressure being about that existing at a depth of fifteen miles, and the temperature about that which may exist at that depth.[2]

It is possible that for certain periods of time there may be static equilibrium in some parts of the lithosphere, where great stresses may counterbalance one another, and where the pressure may be isostatic. But the history of the earth shows that profound motion has taken place at various times in all parts of the lithosphere exposed to view, and at such times the stresses have not been in isostatic equilibrium. When motion takes place the resultant stress which produces it is the

[2] Adams, F. D. Jour. Geol., 20, 1912, 97.

difference between the pressures in various directions, and this difference may be less than the limit of cohesion of the rock mass, or greater than its cohesive strength. Owing to the high rigidity of many rock minerals a large resultant stress may be sustained by some rock masses without appreciable displacement. If, however, the resultant stress becomes greater, either by reason of an increase of the preponderant stresses, or a decrease in the lesser ones, and eventually exceeds the limit of cohesion of the rock mass, fracture ensues, either molecular or molar.

If the molecules of rock minerals are in a strained condition for a considerable time, readjustment by recrystallization may take place in order to establish molecular equilibrium, the result being some form of metamorphic rock, such as gneiss or schist. This process may be accompanied by partial fragmentation or granulation of the rock minerals, resulting in other forms of metamorphic rocks.

The process of crystallization involves a certain amount of mobility of the crystallizing molecules, as may be observed in the crystallization of any substance from a very fluid matrix and from a highly viscous one. Consequently the recrystallization of rock minerals within the lithosphere is promoted by any agency that increases the mobility of the mineral molecules within the limits of crystallization, that is, below the melting point of the compound. Foremost among such agencies are liquids and gases within the body of a rock, and also the accession of heat.

Upon heating, minerals and rocks expand, the amount of expansion in crystals varying with the crystallographic direction; that is, it is not equal in all directions, as in glass. In calcite and orthoclase, there is an actual

shrinkage in certain directions and expansion in others. The heating of a crystalline rock, therefore, must produce diverse internal stresses in various directions, tending to expand the whole mass. In rocks in which different minerals expand or contract to considerable amounts at very different rates for any particular range of temperature, inequalities of expansion or contraction by different kinds of minerals tend to produce unequal stresses which under some conditions may rupture the coherent aggregation and produce fractures between the crystals. Day and his associates have shown that quartz changes its volume much more rapidly between 575° and 500° C. than between 500° and 0° C.; in the first case its change is 2.4 per cent; in the second, 2.8 per cent of its volume at the lower temperature in each case. Above 575° the change in volume is slight, and in the reverse direction to a slight extent; followed, after the inversion of quartz to cristobalite, by a rapid increase in volume as the melting point is approached.[3] In case the component crystals were parallelly oriented the resultant rock expansion would be different in different directions, but in most rocks crystals occur in all possible orientations, so that the resultant expansion is the same in all directions.

The density of minerals and rocks varies inversely as their volumes. The heating of rocks reduces their density until their component crystals pass into the amorphous or glassy state, when there is a more or less pronounced change of volume and of density. This is shown by the accompanying list of densities for some minerals and rocks, and for their glasses at atmospheric temperatures. The increase in volume of these sub-

[3] Day, A. L., Sosman, R. B., Hostetter, J. C. Am. Jour. Sci., 37, 1914, 1.

stances, when crystals and glasses are compared, is greatest in quartz, in which case it is 19.73 per cent, and least in anorthite, in which it is 2.41 per cent. Consequently, the greatest changes for rocks are for highly quartzose granites, and the least changes for rocks rich in anorthite.

Since the amorphous, glassy phases of these substances expand upon heating, the volume of molten magmas at the time of crystallization must be greater than that of their cold glasses, and the difference between the volumes of these liquids and those of the corresponding cold rocks must be greater than the percentages just given. In the case of the diabase, or basalt, from near Fairview, New Jersey, the difference between the volume of the magma at 1250° C. and that of the cold rock has been estimated by Sosman to be 12.53 per cent of the liquid phase.

	Crystal	*Glass*	*Percentage Increase*	
Quartz	2.650	2.213	19.74	Larsen
	2.663	2.228	19.52	Deville
Enstatite	3.175	2.743	15.74	Larsen
Diopside	3.275	2.830	15.71	Larsen
Adular, St. Gotthard	2.575	2.370	8.65	Douglas
Albite, Ab, laboratory	2.605	2.382	9.36	Day and Allen
$Ab_2 An_1$, laboratory	2.660	2.483	7.18	Day and Allen
$Ab_1 An_1$, laboratory	2.679	2.533	5.76	Day and Allen
$Ab_1 An_2$, laboratory	2.710	2.591	4.59	Day and Allen
Anorthite, An, laboratory	2.765	2.700	2.41	Day and Allen
Leucite, Vesuvius	2.480	2.410	2.90	Douglas
Quartz-porphyry, Montreuillon	2.576	2.301	11.95	Delesse
Granite, Flamanville	2.680	2.427	10.42	Delesse
Fine-grained granite, Saint Brieuc	2.751	2.496	10.21	Delesse
Granite, Peterhead	2.630	2.376	10.69	Douglas
Granite, Shap Fells	2.656	2.446	8.58	Douglas
Hornblende-granite, Coralvilliers	2.643	2.478	6.65	Delesse

	Crystal	*Glass*	*Percentage Increase*	
Syenite, Plauen . .	2.724	2.560	6.40	Douglas
Diabase, between Fairview and Granton, N. J. .	2.985	2.778	7.48	Sosman
Diorite, Guernsey . .	2.833	2.680	5.70	Douglas
Gabbro, Carrock Fell .	2.940	2.791	5.41	Douglas
Anorthite-basalt, Mt. Hecla	2.844	2.718	4.63	Delesse
Dolerite, Whin Sill . .	2.925	2.800	4.46	Douglas
Olivine-dolerite, Clee Hills	2.889	2.775	4.14	Douglas

The heating of rock minerals reduces their elasticity or rigidity so that they may be deformed more readily than at lower temperatures under the same pressures, for it is to be expected that isostatic pressure operates in the opposite manner to heating, and counteracts its effects to a greater or less extent. Since rock minerals expand on melting, increasing pressure should necessitate greater heating to produce liquid phases of these substances; that is, their melting points should be raised by increasing pressure. Investigations by J. Johnston and L. H. Adams show that the melting points of lead, cadmium, and tin, which, like the rock minerals, expand on heating, are raised uniformly with increase of pressure up to a temperature of 400° C. and a pressure of 2,000 atmospheres, which is as far as experiments were carried. That is, the change of melting point with pressure is a linear function of the pressure, and its values may be represented by a straight line. There is no evidence that the oft-cited statement by Tammann that this law does not hold for high pressures is based on observed facts. It appears to be in error and to be wholly misleading. The rate of change of melting point with pressure differs with the substance, and has not been determined for silicate compounds that form rock minerals. However, it may be reasonably assumed that

their melting points are raised with increasing pressure, so that at considerable depths within the earth their melting points will be higher than at the surface, but it is probable that the actual increase in degrees will not be great. The melting points of the common rock minerals at atmospheric pressures are given in the accompanying table:

Corundum	1865° C.	Hempel
Zircon	1760	Joly and Cusack
Tridymite	1625	Day and others
Quartz	1600	
Anorthite, An	1550	artificial
Lime-soda-feldspars	$Ab_1 An_5$	1516	"
	$Ab_1 An_2$	1477	"
	$Ab_1 An_1$	1430	"
	$Ab_2 An_1$	1375	"
	$Ab_3 An_1$	1340 approx.	"
Albite, Ab	1100	
Orthoclase, Arendal	1190	Doelter
Sanidine, Drachenfels	1140-1150	"
Leucite	1275-1280	"
Nephelite, Norway	1090-1100	"
Sodalite	1030	"
Analcite	880-890	"
Lepidomelane	1130-1135	"
Biotite, Vesuvius	1155-1160	"
Muscovite	1255-1260	"
Garnet, melanite	925-935	"
Olivine, Egypt	1390-1395	"
Fayalite	1055	"
Diopside	1395	artificial
Enstatite, Bamle	1375-1380	Doelter
Hypersthene, St. Paul	1185-1195	"
Augite, Mti. Rossi, Etna	1165-1170	"
Aegirite, Langesurd fjord	930-945	"
Hornblende, Vesuvius	1085	"
Arfvedsonite, Warjakasik	920	"
Magnetite	1195	"
Hematite	1360	"
Titanite	1200	"
Apatite	1270	"
Fluorite	1387	Day et alii

From this it is seen that most of these minerals melt at temperatures between 900° and 1500° C., the highest being less than 1900° C. However, it does not follow that rock magmas composed of these minerals in liquid forms were as hot as these temperatures when they were erupted through the lithosphere, although they are known to have been completely liquid, that is, amorphous. They may have been hotter in some cases, but there are abundant evidences that they were not so hot in a great many instances.

In the case of the basalt from Fairview, New Jersey, Sosman and Merwin have shown that while the augite in the rock melts slowly at 1150° C., the feldspars beginning to melt at 1200° and being completely fused only at 1300°, yet the magma of the rock when fluid enclosed fragments of sandstone, composed of orthoclase, feldspar, and quartz, without fusing them along the contact surface, although the orthoclase in the sandstone fuses at 1150° C. From this it appears that the basalt magma flowed at a temperature below the melting points of its component minerals.[4]

Many dikes of granite and quartz-porphyry magmas have been intruded into other rocks without fusing them along the contact, although the melting point of the quartz in the igneous rock is much higher than that of minerals in the rocks traversed by the molten magmas. Indeed, it is well known that the difficultly fusible quartz in granite crystallizes after the crystallization of minerals with lower melting points. Moreover, investigations in the laboratory have shown that quartz crystals form in crucibles at temperatures below 800° C., and that above this point silica assumes another crystal

[4] Sosman, R. B., and Merwin, H. E. Jour. Wash. Acad. Sci., 3, 1913, 389.

phase, cristobalite, which is the stable form of silica at sustained temperatures above 800°. Further, the phase of quartz, which is common to pegmatitic granite, must have crystallized at temperatures below 575° C. From these facts it must be concluded that rock magmas are in many instances liquid at temperatures considerably below the melting point of the minerals that crystallize from them. They are, in fact, mineral solutions behaving like other solutions with which we are more familiar, one of the chief characteristics of which is that the melting point of the mixture of two or more substances in solution is lower than that of each substance singly; in other words, that one substance dissolves in another at a temperature lower than its melting point. Familiar examples of this principle are fluxes used in metallurgical processes and in some blowpipe tests.

A common substance whose presence lowers the melting point of rock minerals and increases the liquidity of molten magmas is water, or its gas, which is universally present in lavas and magmas of igneous rocks. It is a potent factor in the whole volcanic problem, and its rôle is varied; in part chemical, entering mineral compounds under different conditions of pressure, temperature, and chemical equilibrium; in part, its action may be considered purely physical, affecting the liquidity of magmas, their crystallizing temperatures, and under certain conditions appearing as an expanding gaseous constituent.

No quantitative determinations have been made as to its effect on the viscosity and melting points of actual rock magmas, and its effectiveness is known in a general way only. G. W. Morey has shown that amorphous potassium silicate, $K_2Si_2O_5$, which may contain from 8 to 25 per cent of H_2O, is a hard glass at atmospheric

temperatures, but with increasing percentages of H_2O becomes a stiff paste, and finally a very viscous solution like water glass. The melting point of anhydrous $K_2Si_2O_5$ is about 1015° C., but the addition of 8 per cent of H_2O lowers the melting point to about 500° C.[5] Under considerable pressure within the earth at the temperatures of molten magmas, above the critical temperature of water when alone, it is possible that much, if not all, of the water in a magma may be in combination with the silicate compounds, or with silica. It does not follow that it exists in a gaseous state because the temperature is so high. There are mineralogical evidences to this effect, and the investigations of Morey show that such compounds exist above the critical temperature and pressure of water gas.

Small amounts of water in rock magmas undoubtedly render them fluid at temperatures considerably below the melting point of the rock minerals; and slightly more water probably renders them highly liquid and capable of penetrating extremely thin fissures in heated rocks. The crystallization of a portion of a magma into anhydrous minerals concentrates in the remaining liquid portion the water that may have permeated the whole magma, increasing its fluidity, and further lowering the melting points of the mineral compounds still in solution. In some instances a differential flow of this portion of a magma takes place, entering fissures and forming veins and dikes of rocks having the composition of those portions of large bodies of magma that crystallize last under ordinary circumstances. Such rocks are pegmatites and aplites of various kinds. It is in this way that the crystallization of quartz in granitic rocks is

[5] Morey, G. W. Jour. Am. Chem. Soc., 36, 1914, 225.

explained, a mineral, one phase of which is unstable at temperatures above 800° C., and another unstable above 575°. It is commonly associated with mica and hornblende, silicates containing hydrogen or hydroxyl as an essential constituent.

However, since quartz is usually one of the last minerals to crystallize in granitic rocks, its formation does not indicate the temperatures at which granitic magmas may have existed when they were erupted before crystallization began. But when quartz crystals were present at the time of eruption of a magma, as is the case with many porphyritic lavas, such as rhyolite, the temperature of the flowing magma must have been such that quartz crystals could exist in it; that is, it must have been below a temperature corresponding to 800° C. at atmospheric pressures.

It is important to notice the matter of pressure in this connection, for it should affect the transition point between two phases of a substance in a manner similar to its effect on the melting points. Since quartz, having a density of 2.66 at atmospheric temperatures, passes into the lighter mineral, cristobalite, with a density of 2.27 to 2.34, upon being heated above 800° C., it is to be expected that increasing pressure would tend to maintain the denser phase at increasingly higher temperatures, but no investigations have been made as yet of this relationship. It is quite possible that the inversion temperatures of different phases of various compounds that have been determined in the laboratory under atmospheric pressures are not exactly those that obtain under higher pressures. However, it is probable that the differences due to changes of pressure are not great when expressed in degrees of temperature.

So far we have been considering rocks chiefly with

respect to the physical characteristics of their component mineral crystals, let us now consider igneous, or volcanic, rocks with special reference to their liquid phases, that is, the lavas or magmas that are the active mobile factors in volcanism. Since molten magmas, or volcanic lavas, flow upward from deeper parts of the earth than those in which they solidify into rock bodies, they are materials from deeper portions of the earth than the deepest parts exposed at its surface in consequence of faulting and erosion. Their source is probably located at the base of the outer zone, which has been called the lithosphere, although this may depend upon precise definitions of magmas and rocks.

Our knowledge of rock magmas rests upon observations of molten lavas in craters and as flows from volcanoes and fissures; on the study of melted igneous rocks in crucibles in laboratories; and on the study of the solidified masses in the form of igneous rocks. From these sources of information we know something of the temperature of molten magmas after they have reached the atmosphere, and the temperatures at which they melt in crucibles; also something of their viscosity or liquidity at such temperatures and under atmospheric conditions. We know the chemical composition of the rock masses into which they solidify, and can infer the composition of the molten magmas by taking into consideration the probable nature of the volatile constituents that escaped in large part at the time of crystallization. For it must always be remembered that the volatile constituents, water, sulphur, chlorine, fluorine, carbon compounds, and others in smaller amounts, while they play an insignificant part in the composition of the fixed mineral compounds in most igneous rocks, are potent factors in liquid magmas, both

chemically and physically, affecting the molecular mobility and the chemical equilibrium of the compounds in solution. For these reasons the behavior of melted magmas in open crucibles is not exactly the same as that of rock magmas as they exist under high pressures within the earth, where greater volumes of the volatile constituents are held in solution. However, since the fixed mineral components of igneous rocks form in most instances more than 95 per cent of the mass in each magma, they must determine the physical and chemical characteristics of molten magmas, which are modified to a greater or less extent by the small percentage of volatile constituents.

The viscosity of rock magmas varies greatly with their composition at temperatures near the melting points of their preponderant constituents. Melts of quartz, orthoclase, or albite are extremely viscous at temperatures just above their melting points. Day and Allen found that orthoclase passed from the crystal to the amorphous molten condition with almost no distinction in viscosity.[6] The amorphous phase was as stiff as the crystal phase at the transition temperature. Melts of quartz, orthoclase, or albite are so extremely viscous as they approach the temperature of crystallization, that there is not enough molecular mobility in the molten mass to permit the molecular movement necessary to orient the molecules into crystal arrangements. The melts solidify into amorphous glasses; that is, the liquids solidify without crystallization, become solid or rigid liquids, so to speak. The presence of some substance that renders melts more liquid at the crystallizing temperatures for quartz, orthoclase, or albite, is

[6] Day, A. L., and Allen, E. T. Carnegie Institution of Washington, Publ. No. 31, 1905.

necessary for their crystallization. In rock magmas composed chiefly of these compounds there are small amounts of other constituents, and the crystallization of quartz, orthoclase, or albite takes place. Such magmas form some kinds of granite, quartz-porphyry, and rhyolite lavas.

On the other hand, calcium-feldspar, anorthite, is quite liquid just above its melting point, and crystallization takes place readily in melts of the pure compound in open crucibles. The same is true of augite, olivine, and the more calcic of the lime-soda-feldspars, so that melts of mixtures of these compounds are quite liquid at temperatures just above their crystallizing points, and readily pass on cooling into completely crystallized masses. Rocks having such a composition are gabbros and some basalts. The presence in magmas of these rocks of constituents rendering the magmas more mobile permits freer molecular motion than in granitic magmas under like conditions, resulting in larger individual crystals, that is, in coarser-grained rocks.

The molecular mobility of magmas is increased by heating, but the actual variation of viscosity with temperature has never been determined for rock magmas. In fact, the whole matter of viscosity and its quantitative definition is an outstanding problem in physics. The action of pressure on the viscosity of magmas has never been investigated. It should affect it in the opposite manner from that in which it is affected by heating, but probably to a very much smaller extent. However, the existence of very high pressures within the earth at greater and greater depths makes it necessary to keep in mind its possible influence on viscosity, whereas the possibility of very high temperatures within the earth is open to very great doubt, and

as it is a matter on which there is no definite information, there is room for a very wide difference of opinion as to the internal temperature of the earth.

As to the actual temperatures of volcanic lavas at the surface of the earth there are very few direct determinations. The most recent have been made by Day and Shepherd on lava in the crater of Kilauea, which proved to be 1000° to 1185° C. at the surface of the central boiling pool. Doelter has determined the temperature of Vesuvian lava at 1000° to 1070° C. Bartoli has determined the Etna lava of 1892 at 970° to 1060° C. Basalt lava on Mauna Loa has been seen to issue at "white heat," possibly about 1500° C. Beyond observations of this kind nothing is definitely known as to the actual heat of molten lavas within the earth.

Inferences may be drawn from evidences as to the apparent melting of rock minerals which have been in contact with igneous magmas, but the question arises in every instance as to how far the phenomenon is one of melting, and how far it may be a case of solution in a highly heated solvent. Consequently, such inferences must be treated with caution. For example, in rare instances quartz and orthoclase have been melted near the contact of granite with a dike of basalt, and have been subsequently chilled to glass which permeates spaces between unmelted crystals of the same minerals in such a manner as to indicate that the rock was highly fractured before, or at the time of, the basaltic intrusion; and since such occurrences bear evidences of having happened near the surface of the earth, it is probable that the fractured granite was charged with water, or an aqueous solution, which aided the mutual solution of quartz and feldspar to form the glass between the fragments. It does not follow that the basaltic lava was

superheated to such an extent that it could melt quartz at some distance from the wall of the dike.

As to the chemical composition of rock magmas, there is considerable variation within certain limits which determine the range of the mineral characters of all igneous rocks. Molten lavas are solutions of silicate compounds in one another; in some instances with notable amounts of uncombined silica, forming quartz; in others with relatively large amounts of iron oxides, forming magnetite. In rare instances apatite is abundant; in others, certain spinels; and in others, sulphides. But there are no igneous rocks in which carbonates form primary, or pyrogenetic, minerals; although in certain instances calcite has crystallized from magmas in such a manner as to appear to have been taken up by them along their contact with limestones. Moreover, it may be said that there are no igneous rocks having the composition of certain sedimentary rocks which would form molten fluids if heated to the temperature of some volcanic lavas. Assertions that igneous rocks have been derived from sediments by fusion ignore this simple chemical evidence to the contrary.

Igneous magmas consist almost wholly of the following elements: oxygen, silicon, aluminium, iron, magnesium, calcium, sodium, and potassium, with small amounts of titanium, hydrogen, and other elements. In chemical analyses, the percentage amounts of these constituents are commonly stated as oxides, but in magmas they probably exist as compounds corresponding more or less closely to mineral molecules.

There are no fixed relations between the amounts of these compounds in volcanic lavas. No body of lava is absolutely homogeneous in composition, and no two rock analyses are exactly alike. Rock magmas are mixed

solutions of mineral compounds, mostly silicates. These compounds may be considered as belonging to a few mineralogical groups, such as the feldspars, micas, amphiboles, pyroxenes, and others; but each of these groups is itself a series of chemically variable compounds, so that the possible combination of the seven or eight principal elements is manifold, and the chemical relationships within the molten magmas are highly complex.

Without entering upon a discussion of these relationships, which affect the mineral composition of igneous rocks, we may consider certain general chemical features of rock magmas which bear more directly on the problem of volcanism. These have to do with the character and origin of series of igneous rocks in separate localities in various parts of the earth, comagmatic series; and with chemical differences between rock series in different regions, that is, with different petrographical provinces.

The igneous rocks occurring together in any region of volcanic activity form a series of varieties differing gradually in chemical composition from one extreme to another, the intermediate varieties being the more abundant and the older eruptions in many instances. To this rule, however, there are many apparent exceptions owing to the incompleteness of series, because of the lack of exposure of a whole series in a particular region; younger lavas covering older ones in some localities, or parts of a series having been carried away by erosion.

In many regions lavas of intermediate composition are andesites, their coarse-grained forms being diorites, quartz-diorites, some varieties being commonly called granite. Andesites grade on the one hand into more

siliceous lavas, dacites and rhyolites, whose coarse-grained forms are granodiorites and granites; and on the other hand they pass into less siliceous lavas, basalts, or their coarse-grained equivalents, gabbros. In some regions there are other varieties, trachytes and syenites, phonolites, and so on. In general, volcanic series consist of intermediate varieties with more siliceous and less siliceous extremes.

The repeated occurrence of such series of lavas in many volcanic regions, and the fact that in most of them different kinds of lavas were erupted in a more or less definite order, or succession, led Scrope, Dana, Darwin, and others to the conclusion that the variations in composition resulted from some process of differentiation of a molten magma that underlay the region, and was the parent magma, so to speak, from which all the volcanic magmas of the series had been derived. Such a rock series, then, would be comagmatic, or congenetic.[7]

This conception has been substantiated by closer study of the constituent minerals and of the chemical characteristics of series of rocks from different regions. It has been found that there are chemical features peculiar to certain series, such as the relative proportions of certain elements, as sodium and potassium, and it has come to be generally accepted that the various kinds of igneous rocks belonging to one period of volcanic eruption in any region have been derived from some parent magma, peculiar to the region, by processes of differentiation that have caused the concentration of

[7] Scrope, G. P. *Volcanos,* London, 1825, 21. Darwin, C., *Volcanic Islands,* London, 1844, 117. Dana, J. D., U. S. Expl. Exped., 1838-1842, Wilkes, Philadelphia, vol. 10, 372. For other references see Iddings, J. P., *Origin of Igneous Rocks,* Bull. Phil. Soc., Washington, 12 (1892-1894), 1895, 89.

some of the mineral compounds in parts of the magma that have flowed at different times, and have solidified into different kinds of rocks. There are various opinions as to how such separations have taken place, but a very general agreement among petrologists that they have done so.

However, there are those who consider that a large part of the variation in the composition of lavas has arisen from the admixture of mineral matter by solution of rocks through which lavas have been erupted; a conception within the bounds of abstract possibilities, if magmas were sufficiently heated at the time of their eruption to permit of considerable melting, solution, and diffusion of the dissolved rock material, and if the chemical composition of the magma and of the rocks, supposed to have been dissolved, were such that their mixture would produce a lava having the composition of one for which such an origin has been claimed.

Mixtures of such a character do occur in some localities, along the contact between certain intruded magmas and the wall rocks, and can be recognized as blended material, but the volume of the blended rocks is relatively small when compared with the volume of the intruded body with which they are associated.[8] Large zones of highly metamorphosed wall rocks are usually adjacent to immense bodies of intrusive rocks, which in some instances are exposed over large areas adjacent to the metamorphic rocks, in others are partly subjacent to them, and of unknown extent.

The overwhelming evidence of innumerable exposures

[8] Lacroix, A. *Comptes Rendus,* 123, 1896, 1021; Bull. Serv. Carte géol. France, No. 64, 1898; *Livret Guide des Excursions en France,* 8e Congrès géol. Intern., Paris, 1900, No. 3, 15. Adams, F. D., and Barlow, A. E., Dept. Mines, Ottawa, Mem. 6, 1910, 308.

of contacts between intruded rock masses and wall rocks of different kinds shows that, in the greater part of the lithosphere exposed to view, the blending by melting and solution of wall rock and molten magma has not taken place to any considerable extent. Dikes of granite traverse beds of sandstone, limestone, and shale without changes in the chemical composition of the granite at the contacts with these different bodies, such as should be expected, if they had been dissolved by the granite. From this we may conclude that in such parts of the lithosphere the intruded magmas were not hot enough to produce the effects claimed by the hypothesis mentioned.

The fusion and mixture of rocks near the contact with igneous intrusions, which have been described by Sederholm as having taken place in Finland within pre-Cambrian conglomeratic formations, presumably at great depths, is an example of what may happen under proper conditions, but which has not happened generally in all other regions of similar pre-Cambrian rocks, as he has stated after studying the relations between igneous intrusions and ancient crystalline schists in the region north of Lake Superior, where, according to Van Hise and Leith, granitic bodies appear to be normal igneous intrusions without evidence of fusion of adjacent rocks.[9]

Metamorphism of wall rocks along the contact with some intrusive magmas is common, and results from heating and infiltration of solutions escaping from the igneous magma. It is located within the body of the wall rock, or in separated fragments of it which may have been surrounded by the intruded magma. Where

[9] Van Hise, C. R., and Leith, C. K. U. S. Geol. Survey, Bull. 360, 1909.

wall rock has been shattered into innumerable small fragments there may have been an intimate mixture of magma and fragments that have become more or less completely metamorphosed, but it seldom happens that there has been anything like a molecular mixture of magma with the chemical constituents of the wall rock, except in a very narrow zone along the contact in comparatively rare instances. It is more probable that in cases where the wall rock was greatly shattered at the time of intrusion of a molten magma the fragments would be carried along by the moving liquid and would appear as inclusions of displaced rock, which are of common occurrence.

The blending of two hot magmas within one conduit, or of a molten magma with one that has almost completely crystallized, but is still very hot, producing hybrid rocks, has been described by Harker. It is not the same process as that commonly assumed to have taken place in the formation of rock mixtures. Hybrid rocks occur on the Isle of Skye, and according to Harker were formed by the more or less intimate welding and solution of granite and gabbro whose magmas were intruded almost synchronously into fractures in other rocks which they did not dissolve, and with which they did not blend.[10]

The lavas or magmas in a comagmatic series have chemical compositions such as may be derived by processes of partial separation of a mixed solution of mineral compounds, and do not correspond to what should be expected to be their compositions if molten magmas dissolved considerable quantities of heterogeneous assortments of wall rocks.

[10] Harker, A., and Clough, C. T. Geol. Survey, Great Britain, Memoir, Tertiary Igneous Rocks of Skye, 1904.

Comparison of the series of igneous rocks occurring in different regions convinced Vogelsang, Judd, and others that there are mineral and chemical features peculiar to rock series in different regions that are sufficient to distinguish them from one another, and which indicate that there are fundamental chemical differences between the magmas from which the various series of rocks were formed. Regions so characterized have been called petrographical provinces.[11] The first distinctions pointed out were obvious differences in the mineral composition of some rocks in contrasted series, such as the occurrences of nephelite and leucite in certain rocks in Bohemia, and the absence of these minerals in corresponding rocks in Hungary. These minerals are alumino-silicates of sodium and potassium, and being easily identified by microscopic study of rock sections became criteria by which differences in some petrographical provinces were recognized. The psychological effect of employing this simple method of diagnosis has been to contrast those series in which these minerals occur with series in which they do not occur, and to consider them as forming two categories of rocks to either one of which all rock series must necessarily be referred. Hence the so-called "alkalic" and "subalkalic" series, and the highly artificial misnomers, "Atlantic" and "Pacific" hordes.

When it is remembered that the essential chemical differences between nephelite and albite feldspar and between leucite and orthoclase feldspar rest in the relative amounts of silica and not in the alkalies, and that the soda- and potash-feldspars are common to all series of igneous rocks; and further, that variations in

[11] Judd, J. W. Quar. Jour. Geol. Soc., London, 42, 1886, 54.

the amounts of silica are also common to all rock series, the insignificance of the mere presence or absence of nephelite or leucite in rocks is apparent. Sodium and potassium are very characteristic chemical constituents in many rock series, and their relative proportions may be highly significant criteria in the comparison of various rock series, but there are other chemical constituents that characterize rock magmas, which in some instances are more conspicuous than the alkalies. They are magnesium, calcium, and iron, besides aluminium; and the most abundant of all is silicon. These constituents act in a measure as independent variables in the mineral equations of rock composition, and the crude inadequacy of a division of the manifold series of rock variations into two categories on a basis of the presence or absence of a part of the functions of only two of the seven principal variables should be evident on a moment's reflection.

There are in fact many rock series differing to greater or less extents from one another, that is, many different petrographical provinces, whose exact definition in terms of so many variables is a complex undertaking which has not been attempted by any petrographer up to the present time. An approach to such a definition may be made by representing variations of the chemical constituents of rocks in contrasted series by means of diagrams in which the principal oxides determined by chemical analysis are plotted with respect to variations in silica. In this manner it can be shown that series of rocks from neighboring districts of a large volcanic region like the Yellowstone National Park differ from one another by the relative and total amounts of soda and potash in rocks of each series, as well as in the relative amounts of other constituents. The rocks of

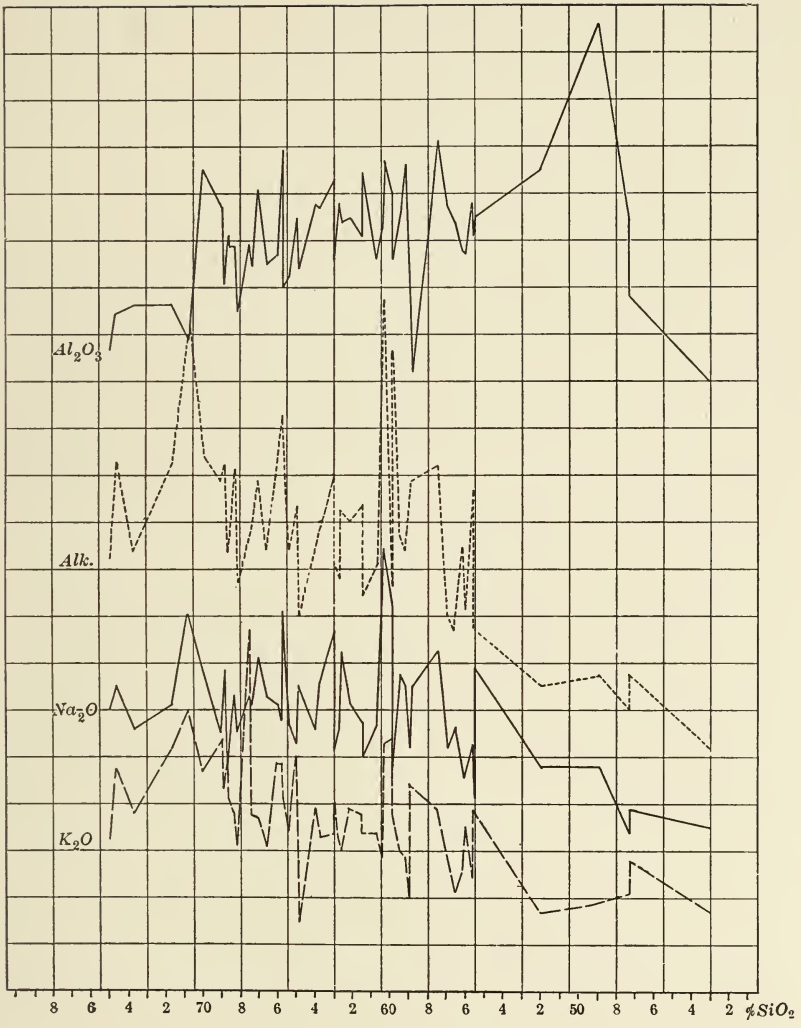

FIG. 43. MOLECULAR PROPORTIONS OF ALKALIES AND ALUMINA IN ANALYSES OF IGNEOUS ROCKS IN SOUTHWESTERN COLORADO

these two series bear like names according to customary methods of classification and would not be distinguished from one another in ordinary petrographic descriptions. In like manner slight but fundamental chemical differences may be shown to exist between the rocks just mentioned and the igneous rocks of southwestern Colorado, and between these and the lavas of Mount Shasta and Lassen Peak in California, where the ratio of potash to soda is characteristically low.[12] Differences between the alkalies in rocks of Colorado and in those of the Shasta-Lassen district in California are shown in Figures 43 and 44.

Series of rocks that are almost identical occur in widely remote parts of the earth, such as those of the Great Basin of Utah and Nevada and rocks of Hungary; also the lavas of the Hawaiian Islands and those of the Island of Réunion, according to A. Lacroix. In the comparison of series of igneous rocks from all parts of the earth it must be remembered that the same chemical constituents occur in all of them, that the differentiated varieties in each series consist chiefly of the same kinds of minerals or mineral groups, and that the distinguishing characteristics are quantitative differences in the relative amounts of the common chemical constituents. The combinations of these constituents into mineral compounds are more numerous than the elements of which they are composed, so that the mineral variations among igneous rocks appear to be greater than the chemical variations, but even in this respect the chief distinctions among the rocks and the series of rocks are quantitative.

It follows from this that while rock series in some

[12] Iddings, J. P. *Igneous Rocks*, 2, 1913, 479.

petrographical provinces may differ from those in other provinces by containing rocks differently named, in some instances because of the presence of nephelite or leucite, it happens that there are provinces with rock series that differ from one another chiefly in the relative amounts of the same kinds of rocks, having like names. Thus one rock series may consist chiefly of the more siliceous varieties, and another chiefly of the less siliceous ones. Such quantitative distinctions may be difficult to establish because of the incompleteness of the information obtainable regarding the quantities of different kinds of rocks in any region, but there are instances in which the contrasts are so pronounced that quantitative differences are obvious.

The significance of differences in petrographical provinces is of fundamental importance in the problem of volcanism. For if igneous magmas have been erupted from considerable depths within the earth, and have reached their positions as solidified rocks without material addition of substance from the rocks through which they passed, as appears to have been the case, then they represent the composition of that portion of the earth from which they flowed. Differences in the composition of rock series in various regions should indicate differences in the composition of the earth beneath these regions, that is, heterogeneity of the body of the earth; not as to kinds of elements present, but as to their relative amounts.

The application of this principle to the problem of the general composition of the earth beneath large areas of its surface must be made with due caution, for it is to be remembered that a small body of rock of any kind does not constitute a rock series, or establish the petrographical character of a province. Similarly, a small

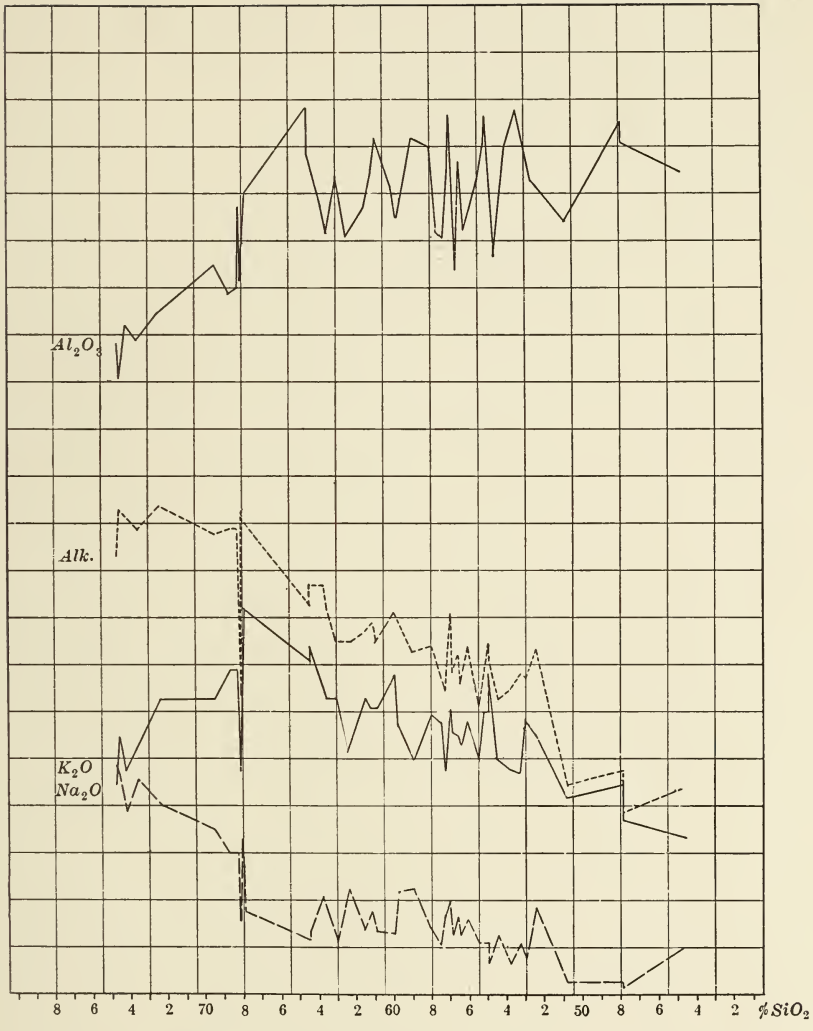

FIG. 44. MOLECULAR PROPORTIONS OF ALKALIES AND ALUMINA IN ANALYSES OF IGNEOUS ROCKS OF MOUNT SHASTA AND LASSEN PEAK, CALIFORNIA

number of igneous rocks do not necessarily represent a complete series, or a major part of one. The greater part of a highly differentiated series may have been removed by erosion, or may not be exposed in a particular region. Large series of igneous rocks representing long-continued eruptions over a wide area should form the basis of deductions regarding the composition of underlying portions of the earth, and judgments should be based on numerous chemical analyses as the only present approximation to quantitative data.

The fallacy of basing conclusions on general statements regarding the rocks of any region may be illustrated by the impressions conveyed by such rock names as "granite" and "basalt," as commonly employed in geological descriptions of regions. For example, it is customary to speak of the granites of the Sierra Nevada as constituting the chief rocks of the mountains. It is also customary to speak of the "Columbia River basalts" as covering vast areas in the valley of this river, and as forming a large portion of the Cascade Range; and these rocks are thought of as extremes of the rock series of the Pacific Coast region, one being high in silica and alkalies, the other low in silica and rich in lime, magnesia, and iron oxide. It is not commonly noticed that the usage of the words cited is that of geologists in general descriptions of the region, while the interpretation is that of a petrographer reading the words "granite" and "basalt."

The rocks of the Sierra Nevada commonly called granite, while in part granite in a modern petrographical sense, are in very large part granodiorites, some of which have chemical compositions shown by analyses 1 and 2 in the accompanying table; while the Columbia River basalts are lavas with various compositions, a

typical variety of which, the "Yakima basalt," having a thickness of 1,000 or 2,000 feet, one of the largest volcanic formations in America according to George Otis Smith and F. C. Calkins,[13] has a chemical composition which is shown by analysis 3; a similar "basalt" from the Middle Fork of the Teanaway River, Washington, having a composition shown by analysis 4.

	1	*2*	*3*	*4*	*5*	*6*
SiO_2	63.43	59.48	54.50	53.35	61.58	55.53
Al_2O_3	14.20	17.25	14.43	12.90	16.96	17.63
Fe_2O_3	1.54	2.15	2.17	2.64	1.75	2.81
FeO	4.56	4.06	8.80	11.28	2.85	3.59
MgO	2.35	2.67	4.24	2.68	3.67	5.85
CaO	5.51	6.50	8.01	6.96	6.28	8.74
Na_2O	3.49	3.53	3.05	2.83	3.94	3.09
K_2O	2.19	2.27	1.29	1.40	1.28	.92
H_2O	1.65	.80	1.38	2.67	1.30	1.24
TiO_2	.73	.93	1.69	2.44	.49	.56
P_2O_5	.11	.33	.21	.45	.22	.21
MnO	.03	.11	.10	.25	tr	.08
Etc.	.06	.09	.26	.22	.03	.08
	99.85	100.17	100.13	100.07	100.35	100.33

1. Granodiorite, near Bangor, Butte County, Calif. W. F. Hillebrand.
2. Granodiorite, Donner Pass, Placer County, Calif. W. F. Hillebrand.
3. Yakima Basalt, Clealum Ridge, Wash. George Steiger.
4. Basalt, Middle Fork, Teanaway River, Wash. W. F. Hillebrand.
5. Hornblende-andesite, Mt. Shasta, Calif. Stokes.
6. Pyroxene-andesite, Butte Mountain, Plumas County, Calif. W. F. Hillebrand.

These analyses are not very different from one another and might have been made from varieties of lavas, called andesites, two analyses of which are cited for comparison in columns 5 and 6. That is to say, much of the so-called "granite" of the Sierra Nevada, while somewhat more siliceous than the varieties whose

[13] Smith, G. O., and Calkins, F. C. U. S. Geol. Survey, Bull. 235, 1904.

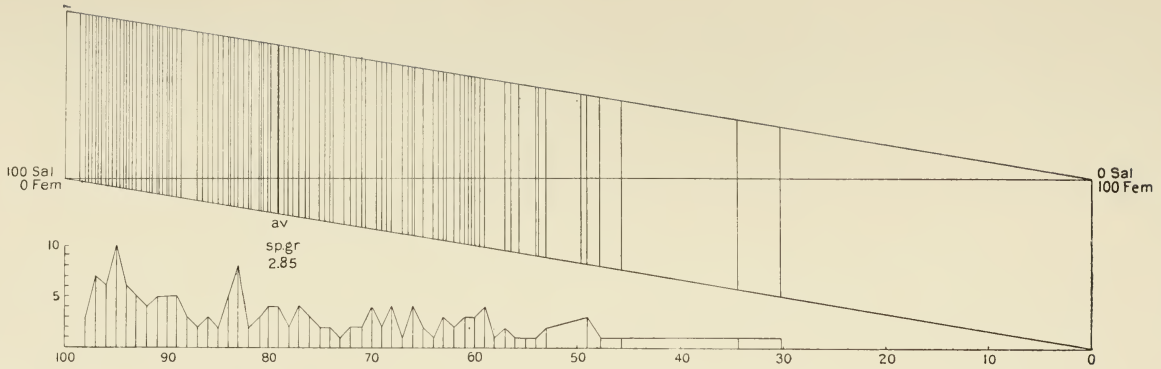

FIG. 45. PROPORTIONS OF SALIC AND FEMIC CONSTITUENTS IN IGNEOUS ROCKS OF CALIFORNIA

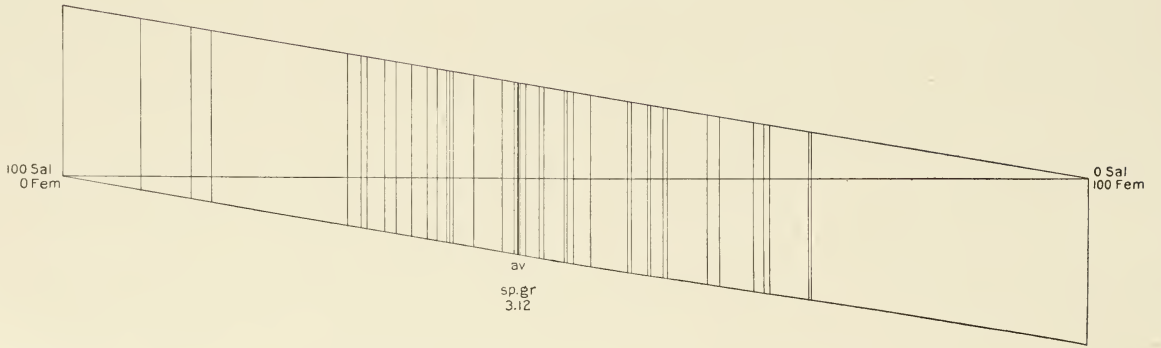

FIG. 46. PROPORTIONS OF SALIC AND FEMIC CONSTITUENTS IN IGNEOUS ROCKS OF THE HAWAIIAN ISLANDS

analyses have been cited, has a chemical composition not very different from large bodies of lava in the region farther north which are commonly called "basalt." A great part of both groups of rocks might be considered as slightly different phases of magmas, which in the form of volcanic lavas in other parts of the Pacific Coast, and in the Andes, would ordinarily be called by one general name, andesite. It is obvious that generalizations based only on petrographical names, without exact chemical or mineral qualifications, may be wholly misleading, or actually false.

Exact quantitative determinations of the relative amounts of the various igneous rocks in any given region are impossible to obtain; however, an impression of the range of their variations, or an approximation to their average composition, may be gotten from a comparison of diagrams representing their chemical constituents, or their possible mineral composition when this is expressed in standard normative minerals, provided a sufficiently large number of representative rocks from any province has been analyzed. This has been done for rock series in the Sierra Nevada in California, in southwestern Colorado, in the Yellowstone National Park, in the Hawaiian Islands, and in other regions.[14]

One method of making such a comparison between the igneous rocks of the Pacific Coast of the United States of America and the lavas of the Hawaiian Islands is shown by diagrams in Figures 45 and 46. The comparison rests wholly on the relative amounts of the salic and femic components of the rocks of these regions that have been analyzed. The salic embrace normative quartz and feldspars; the femic, normative pyroxene, olivine, magnetite, ilmenite, and apatite. In the diagrams the

[14] Clarke, F. W. U. S. Geol. Survey, Bull. 419, 1910.

vertical lines show the proportionate amounts of these two groups of components in each rock analyzed, the lines being spaced along the horizontal axis according to the percentages of these two groups in each rock. From these diagrams it is seen that the rocks of the Pacific Coast are mostly high in feldspars and quartz, and low in minerals containing iron and magnesium, whereas the rocks of the Hawaiian region are largely in the middle of the possible range of variations, and contain nearly equal amounts of salic and femic minerals. The rocks of the first group are richer in quartz and alkalic feldspars; those of the second group are much lower in quartz, and richer in ferromagnesian minerals. That is, the Californian rocks are richer in the lighter minerals; the Hawaiian rocks are richer in the heavier minerals. The position of the average for each series is shown by the heavy vertical line in each diagram. The average from each group of analyses is shown by the accompanying analyses:

	1	*2*
SiO_2	62.20	48.69
Al_2O_3	15.87	14.00
Fe_2O_3	2.12	5.03
FeO	3.46	8.01
MgO	3.93	7.12
CaO	6.06	9.00
Na_2O	3.49	3.55
K_2O	1.92	1.24
TiO_2	.58	2.29
P_2O_5	.27	.49
MnO	.10	.41
	100.00	99.83

1. Average of 195 analyses of igneous rocks from California, F. W. Clarke.

2. Average of 43 analyses of lavas from Hawaiian Islands, Whitman Cross.

The Hawaiian Islands occur in the center of one of the great deeps in the middle of the Pacific Ocean, where the density of the earth has been found to be above the normal density for the surface of the spheroid. The Sierra Nevada rocks form a lofty mountain range on the border of a continent where isostasy demands that the earth should consist of lighter materials, and where geodetic observations have shown that the force of gravity is below the normal.

The relative densities of the rocks that might crystallize from magmas having the compositions of the average analyses just cited are 2.85 for the California average and 3.12 for the Hawaiian. The relative densities of molten magmas corresponding to these averages would probably be somewhat farther apart than the densities of the crystallized bodies, on account of the greater volumetric expansion of highly quartzose rocks when compared with rocks composed chiefly of calcic feldspars, pyroxene, and olivine. If these densities represented the relative densities of the material of the lithosphere beneath each of these regions, and the lithosphere were supposed to be homogeneous from the surface downwards, then the depth of material that would be required to maintain the two regions at approximate altitudes of 5,000 feet above sea level in one case, and 15,000 feet below it in the other, would be about thirty-three miles. However, it is not to be assumed that these figures are anything more than indications that the lavas erupted in different regions, if their average composition in each province could be actually discovered, would correspond closely to the composition of large volumes of the lithosphere beneath these provinces, and would have approximately the

density required to maintain the major inequalities of the earth's surface in these regions.

It is interesting to note that the averages calculated by F. W. Clarke of large groups of chemical analyses representing the igneous rocks of Colorado, the Yellowstone National Park, the Atlantic Coast of North America from Maine to Georgia, and various large areas of the continent of Europe, are each very similar to that of California which has been cited, from which it appears that the relative densities of the corresponding average rocks and magmas for each of these continental regions would be very similar to that calculated for the California region.[15] The relative densities are as follows:

From 195 rocks of California, 2.85
From 137 rocks of Colorado, 2.80
From 113 rocks of Yellowstone Park, 2.85
From 250 rocks of Atlantic Coast, 2.89
From 536 rocks of Great Britain, 2.91
From 231 rocks of Scandinavia and Finland, 2.85
From 420 rocks of Germany and Austro-Hungary, 2.81
From 250 rocks of Italy, 2.86

Steinmann has pointed out the fact that the preponderant lavas in the South American Cordilleras are andesites, dacites, and rhyolites, with quite subordinate amounts of basalt, and that the prevailing intrusive rocks are granodiorites. That is, the average igneous rock of this region is similar to that of the Pacific Coast of North America.[16] On the other hand, the lavas of Réunion in the Indian Ocean, of Tahiti, Juan Fernandez, and other islands in the Southern Pacific, are very much like those of the Hawaiian volcanoes, and

[15] Clarke, F. W. Proc. Am. Phil. Soc., Philadelphia, 51, 1912, 214.
[16] Steinmann, G. *Geol. Rundschau,* 1, 1910, 13.

represent magmas with relatively high densities.[17] The estimated density of the average of twenty-five analyses of rocks from Réunion is 3.12, the same as that of the average for Hawaiian rocks. The density of the average of fifteen analyses of rocks from Tahiti is 2.96, which is probably lower than it should be, because the analyses include a relatively large number of exceptional varieties of rocks comparatively rich in alkali-aluminous minerals.[18]

The correspondence between the general character of large series of igneous rocks in these regions and the general demands of the theory of isostasy respecting the existence of deep oceans and elevated continents is striking, but there can never be any close approach to a quantitative determination of the actual relationship. The requisite data can never be obtained for an absolute determination of the relative masses of igneous rocks in any region, as already said. So far as it goes, the correspondence between the igneous rocks of petrographical provinces and the relative densities of various parts of the lithosphere is in accord with reasonable expectations, on the assumption that igneous magmas represent differentiated portions of deep-seated parts of the earth underlying the regions in which they have been erupted.

[17] Iddings, J. P. *Igneous Rocks,* New York, 1913, 656.

[18] Lacroix, A. *Comptes Rendus,* 154, 1912, 251 and 630; also 155, 1912, 538. Bull. Soc. géol. France, 10, 1910, 91.

CHAPTER V

DYNAMICAL STATUS OF THE EARTH

The physical history of the earth, as recorded in the structure of the lithosphere, indicates that the planet is a rigid, elastic body, complex and heterogeneous. The movements that have affected great masses of the lithosphere, and have formed continents and ocean basins, have been on such an immense scale that the blocks of solid lithosphere involved are vastly larger than the volumes of volcanic lava erupted, though these are measurable in cubic miles in some instances. So that, as Le Conte, Dana, and Suess have pointed out, volcanic activities are subordinate to those that have produced continents and oceans.[1]

The major factors in earth movements are not volcanic in the ordinary sense of the term. Volcanic eruptions are consequences of the major movements, not their cause. It is necessary, then, to consider the possible causes of the major movements, or of diastrophism, within the body of the earth in order to understand the source of volcanic action. What has caused profound displacements in the lithosphere?

The recurrence through countless ages of similar movements in the lithosphere indicates similarity in the exciting causes. Although periodic in behavior, it does not follow that the causes were intermittent in action.

[1] Le Conte, J. Am. Jour. Sci., 4, 1872, 470; 5, 1873, 345; 7, 1874, 167, 259. Dana, J. D., Am. Jour. Sci., 5, 1873, 347, 423; 6, 1873, 6, 104. Suess, E., *Das Antlitz der Erde.*

The periodic yielding of an elastic body to stress may indicate the gradual accumulation of strained conditions within it until they reach the limit of elasticity or of cohesion; when fracture and adjustment of the fragments take place, after which the readjusted system may continue to resist the same kind of stresses that were operative before. What is the nature of the stresses operating within the earth? Are they uniformly active? or are they intermittent?

In approaching this question, we may consider the possibility of equilibrium within the earth's body, and the causes that may tend to disturb it. While equilibrium within the body of a planet in the solar system may not be a physical possibility, an approach to mutual adjustment between various energies that are inherent in its substance, or that react upon it from surrounding space, is conceivable. An apparent example of such equilibrium may be found in the moon, a body that exhibits no evidence of surficial movements or displacements of a magnitude sufficient to be visible from the earth, the circular pits showing no signs of dislocation since the last infall of planetary masses. On the earth, however, changes on a much smaller scale may be taken into account, while evidences of great physical adjustment may also be observed.

A conception of equilibrium within the whirling earth involves the idea of the absence of differential motion among parts of the lithosphere and the mass within; and also the absence of chemical reactions among its components. That is to say, no changes in the earth's volume, and none in the relative positions of the materials composing it, and no changes in the positions and arrangements of the constituent molecules. Such a conception, in its extreme form, is so foreign to our

thoughts regarding the earth, and to our experiences upon its surface, that it seems senseless to consider it other than an abstraction, of no direct bearing on the problem of volcanism, which is a question of the operation of titantic energies.

Nevertheless, the phenomena of volcanism are so inconsiderable when compared with the major movements of the earth at remote intervals, and these displacements are so small when compared with the dimensions and volume of the whole planet, that the dominant thought in connection with the entire body of earth phenomena is one of comparative stability, and of the adjustment of the major forces or energies inherent in the planet's mass. That is, the immense energies within the planet are chiefly in a state of equilibrium, and only a small fraction becomes sensible when the equilibrium is disturbed, as Chamberlin has remarked.

We are led, then, to the consideration of adjustments of energies, and reactions of masses to stresses, that differ greatly in their order of magnitude; and it is the failure to discriminate these quantitative differences that has added confusion to the discussion of a problem which is at best highly complex. The earth may be thought of as a huge mass in comparative equilibrium with respect to its dominant energies, but experiencing disturbances that show themselves in the surficial phenomena already mentioned. What are the dominant energies within the earth, and how may they react on its outer, visible portion?

Of the great body of the earth we know only its size, shape, density, and relative rigidity. Of its chemical composition, physical constitution, and temperature we have no direct knowledge. From the fact that the density of the whole planet is 5.527, while the density

of the known portion of the lithosphere is only about 2.75 or 2.67, it follows that the density of the interior of the planet must be greater than 5.527. Not knowing the thickness of the lithosphere, nor the distribution of matter within the planet, we know nothing definitely as to the distribution of densities within it.

Since the chemical elements and their compounds which occur in the outer portions of the earth have sufficient range in density if they were present in proper proportions, and since spectroscopic study of the sun and other bodies in the universe has revealed no other elements than those common to the lithosphere, with the possible exception of nebulium in some nebulæ, it is reasonable to conclude that the earth consists wholly of known elements. However, their distribution, chemical combinations, and physical phases under the enormous pressures within the earth are matters regarding which there is at present wide diversity of opinion.

A fundamental factor in any theory relating to the character of the earth's interior is its temperature, and of this we have limited and somewhat discordant information, restricted to a very shallow zone of the lithosphere, besides the observed temperature of some molten lavas.

Observations of temperatures within the earth have been made in mines and deep wells, and are far from reliable data as to the actual temperatures of the rock masses at the depths at which observations were taken. These records are usually cited in the form of averages, under the assumption that there should be an approximately uniform distribution of temperature within the earth. It is generally admitted that the temperatures observed are not concordant, and that the rates of increase downward in various localities are not as

regular as might be expected. Some idea of the variability among the observations may be gotten from the diagram (Fig. 47), in which the depths and the temperatures in various localities are plotted. The straight lines correspond to average gradients in the cases cited. It is customary to refer the highest gradients to local heating caused by chemical reactions in deposits of hydrocarbons, such as coal and oil; and to refer the lowest gradients to the cooling effects of bodies of circulating water.

In this connection it is interesting to note the relation between the observed temperatures and the curves representing hypothetical temperatures of the interior of the earth according to several theories as to its origin. In Figure 48, the lower curves correspond to a hypothetical distribution of temperature calculated by Lord Kelvin on the assumption that the globe is cooling from an initial temperature of 3900° C. in one case, and from a temperature corresponding to the melting point of platinum, about 1753° C. in another.[2] According to this hypothesis the internal temperature of the earth is nearly constant below a depth of about two hundred miles. On the other hand, Arrhenius has imagined that temperature within the earth increases at a nearly uniform rate all the way to the center, where its order of magnitude is supposed to be 100,000° C.[3] This hypothetical gradient is represented in the diagram by a broken line. When it is remembered that these hypothetical curves of temperature are extrapolated for distances over 4,000 times greater than those within which the discordant observations were made, the

[2] King, C. Am. Jour. Sci., 45, 1893, 16.

[3] Arrhenius, S. A. *Lehrbuch der Kosmischen Physik,* Leipzig, 1903, 282.

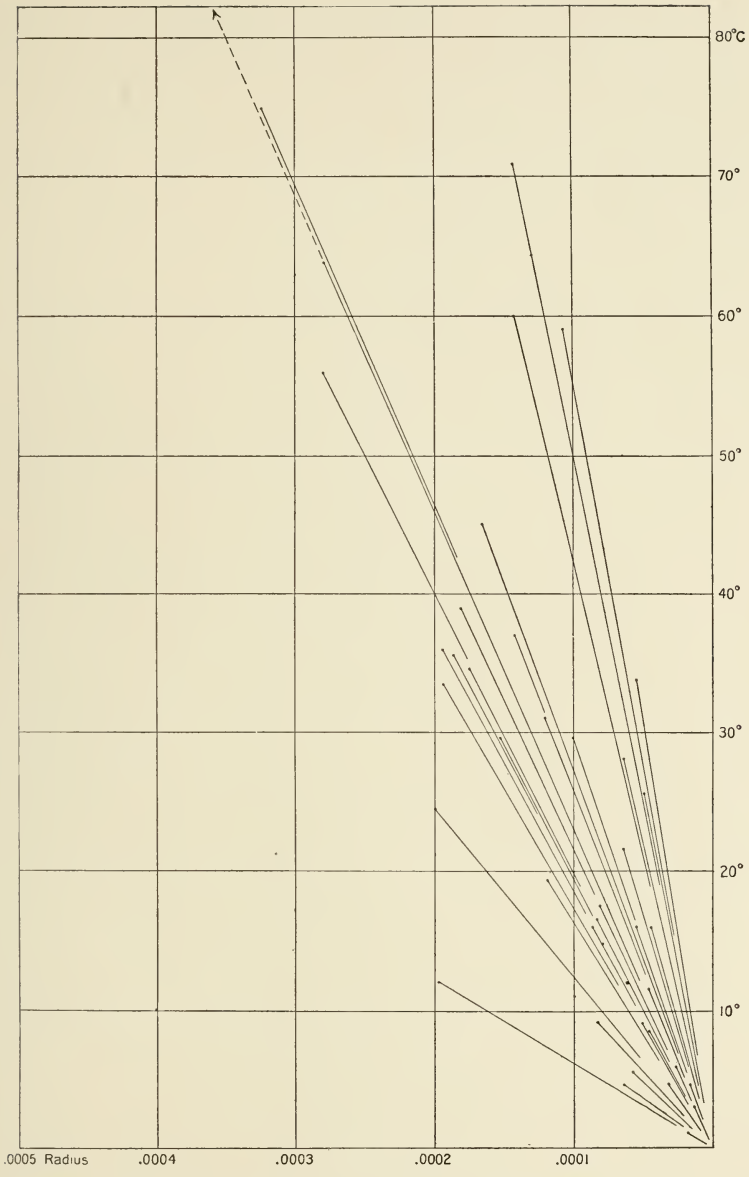

FIG. 47. TEMPERATURE GRADIENTS WITHIN THE EARTH AT VARIOUS LOCALITIES

imaginary character of such methods of estimating the temperature of the interior of the earth is obvious.

From the observed temperatures, it may be inferred that temperature increases still farther downward, and that there are regions in which it is that of molten lavas, which may be as much as 1500° C. It may be inferred also that irregular variations of temperature continue somewhat beyond the depths within which they have been observed. Temperatures on the surface of the earth differ considerably, and the rate of loss in polar regions must be greater than in equatorial ones. Minerals and rocks conduct heat at different rates, but the resultant differences in complex assemblages of rocks must be less than the differences between individual rocks and minerals; nevertheless, there should be appreciable differences in rates of conductivity, or cooling, in different parts of a heterogeneous planet. However, it is questionable whether Dana was justified in allotting to them as great a rôle in the production of the inequalities of the earth's surface as he did in accounting for the formation of continents and oceans.

Conceptions as to the physical condition of the interior of the earth may be obtained by imagining the process of its formation along the lines of the several hypotheses that have been suggested as to its origin. According to the accretionary hypothesis we may imagine the gradual aggregation of discrete particles of matter composed of elements which are known to exist in the earth, which occur in meteorites, and which are present in the sun. These chemical elements we may assume were combined with one another in compounds that were conditioned by the temperature and pressure under which they existed in the nebular state. It may be assumed that

the pressure was extremely small, and the temperature such that the particles were solid compounds, but not necessarily crystallized; for, if we imagine the nebulous matter to have been derived from an exploding sun, the immense suddenness and violence of such an explosion, the tremendous velocity of ejection, and the resultant rarefaction of the material would seem to preclude the formation of highly complex compounds, if any formed, assuming a previous state of dissociation in outer portions of the sun because of high temperatures; and it would seem to prevent the formation of orderly arranged molecules, as in crystals.

The much less sudden chilling of liquid compounds having the composition of silicate minerals produces amorphous glass. So it is to be imagined that a more rapid chilling of any gaseous molecules of chemical compounds, if they had the composition of mineral silicates, would hardly produce crystalline aggregations of molecules, and might even fail to produce in the first instance any molecular aggregations whatever.

Subsequently, through a process that may have been infinitely slow in its earlier stages, there may have taken place an aggregation of molecules, some of which may have been compounded of two or more elements; those having the greater mass acting as nuclei for others; the more massive nuclei attracting others, and being themselves drawn together during their orbital motions within the nebula. Professor Chamberlin has suggested that particles of matter, such as metallic iron and the more ferriferous compounds, by reasons of lower elasticity than some of the more rigid silicates, would experience less rebound upon mutual collision, and because of possible magnetic properties might tend to

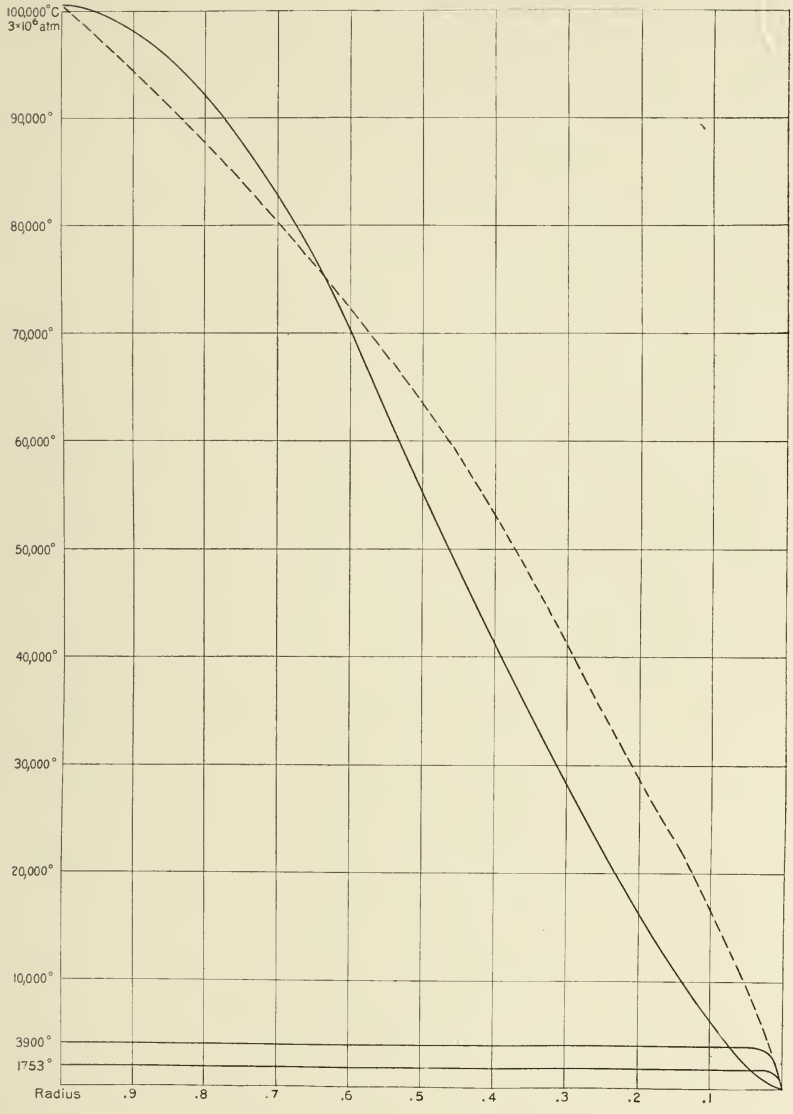

FIG. 48. HYPOTHETICAL CURVES OF TEMPERATURE WITHIN THE EARTH, AND THE CURVE OF PRESSURES ACCORDING TO LAPLACE'S HYPOTHESIS AS TO DENSITIES

aggregate at a greater rate than more elastic and less magnetic particles.[4]

Discrete particles coming together in this manner at low temperatures should form amorphous uncrystallized bodies of heterogeneous chemical composition. Their coherence should be very slight until a sufficient quantity had accumulated to exert pressure upon the interior of a nucleal body. The mutual impact of loosely aggregated matter should scatter the loose material on the surface of the growing nuclei; and in early periods of growth the force of impact should not be great, owing to the smallness of the masses and their comparative proximity to one another. At first, they might coalesce like clouds of dust. Later, they might come together like masses of loose, dry earth. It has been suggested by Professor Pickering that the first and second satellites of Jupiter consist of incoherent dust-like particles; the mass of each being capable of periodic distortion under the tidal attraction of the controlling planet, as though they were whirling clouds or meteoric swarms.[5]

Particles differing from one another in density impinging against such a loosely aggregated nucleus should penetrate it to various depths according to their densities and volumes, that is, their mass and size. The more massive, and the denser, particles should reach greater depths, and in this manner a concentration of denser matter might take place in the central part of a growing nucleus.

Even when the central portion of large nuclei had become compact coherent bodies the outer portions should consist of incoherent matter. Before a growing mass had become great enough to hold an atmosphere

[4] In a letter to the author, dated Chicago, December 2, 1913.

[5] Young, C. A. *A Text Book of General Astronomy,* 1904.

of gas the impact of a lighter aggregation should result in a great displacement of dust as it buried itself within the outer zone of incoherent matter. May not this be the condition of the moon's surface, since no atmosphere or liquid exists upon it? The pits may be depressions in an incoherent outer zone surrounding a dense coherent sphere, as has been suggested by Meydenbauer.[6]

It does not necessarily follow from the hypothesis that the matter forming the moon's outer zone should consist of unmodified nebular particles. They may have experienced more or less aggregation without having become coherent rock-like masses. In places the impact of more or less dense bodies that reached the moon may have compacted the outer material sufficiently to permit it to retain the steep slopes which appear to form some of the pit walls. However, the probable lightness of the material, the slightness of the force of gravity on the moon's surface, and the absence of atmospheric disturbances may account for the permanence of such steep slopes of more or less incoherent material.

The whiteness of the interior of some of the smallest pits, and the great white streaks that extend in straight lines from some of the larger ones, may be due to finely divided matter, which upon the impact of the more considerable satellites was splashed over the surrounding surface, in part concealing its older inequalities. The great furrows that cut across the moon's surface like deep canyons may have been formed by the plowing of dense blocks through loosely coherent material, the blocks being fragments of impinging satellites.

The suggestion that the earth might have been formed

[6] Meydenbauer, A. *Sirius*, February, 1882.

by the aggregation of bodies having the constitution of meteorites is not a form of nebular hypothesis, for it is not conceivable that nebulæ should consist of masses of crystallized minerals whose sizes and arrangement in meteoric bodies are such that they appear to have formed under conditions similar to those under which intrusive igneous rocks have formed within the lithosphere of the earth. Meteorites appear to be fragments of large masses of crystalline rocks, most of them very rich in metallic iron. They appear to be fragments of an exploded planet which had been large enough to have developed within itself molten magmas somewhat like those within the earth.[7] Moreover, they appear to be fragments of that part of a planet in which such coarsely crystallized rocks could be brecciated and cemented together, as in some crushed rocks within the earth, that is, within its lithosphere. For the rupture of that part of a planet which might consist of molten magma would not produce a crystalline rock, but an explosion into pumice dust.

We may imagine, then, the earth in its early stages a huge aggregation of discrete particles of chemical compounds and uncombined elements of the less active kinds chemically, without crystalline structure, in heterogeneous mixture; we may suppose that the central portions consisted of greater quantities of denser matter than the outer portions; that the denser particles were the first to gather together, and that in so doing they attracted and involved lighter matter to some extent, so that the earliest aggregations were mixtures, mostly of matter with the greater densities. Gradually the proportion of lighter matter should increase and the density

[7] Farrington, O. C. Jour. Geol., 9, 1901, 623.

of outer portions of the planet become less than that of the innermost; however, this variation should not be uniform in concentric zones, because of the accession to the planet, from time to time, of large nuclei from the surrounding nebula, each nucleus having its central mass of somewhat denser material. This would account for the heterogeneity that is indicated by the existence of continents and oceans.

What are the possible physical changes that might have taken place within such a central aggregation as the planet increased in size and mass? The one sure result of such a growth would be an increase of pressure, greatest at the center. Rising pressure would produce molecular contact of the discrete particles and the welding of the central aggregation into a coherent, rigid body, without molecular, crystal arrangement, an amorphous coherent mass.

What may have been the chemical equilibrium within such a body, its molecular mobility, and its temperature? Since these conditions are largely dependent on one another, they should not be considered separately. The possible chemical reactions might have been chiefly those that should take place between the elements and compounds which compose rock bodies rich in iron and silicates of magnesium, iron and calcium, like some meteorites; not the familiar reactions that take place in aqueous solutions and in mixtures of chemically active agents. If these more active agents are present in the central mass of the planet, as they may be, it is probable that their percentage is very small, so that the controlling reactions should be those that might take place between the greatly preponderant constituents. The close contact of such chemically inert matter in solid

form at low temperatures should not produce appreciable changes in the chemical equilibrium between them.

The greater the pressure, the closer the contact, and the less chance there would be for molecular readjustment. It is true that laboratory experience has shown that dense metals, like lead and gold, when pressed together diffuse into one another, and the greater the pressure the more rapid the diffusion. This would seem to be promoting a solution of two substances in one another, where solution was accompanied by condensation of volume. This principle applied to the condition of a heterogeneous mixture of dense matter, possibly in large part metallic iron, in the center of the growing earth might promote the diffusion of the less rigid constituents within the amorphous mass.

If the temperature were increased, molecular mobility should increase, and chemical reactions and readjustments of the elements should take place according to new conditions of equilibrium. However, it must be remembered that among the mineral components of rocks there are many instances of false equilibria, crystallized compounds and crystal phases existing for millions of years at temperatures at which they should not be stable. This pseudostable condition indicates extreme sluggishness of physical and chemical reactions in such compounds when in crystal phases. But the material in the center of the growing planet has been assumed to be uncrystallized in the beginning, and might have been somewhat less inert for that reason, since it is known that rock glasses are less stable than crystallized minerals.

What are the possible sources of heat that might coöperate to raise the temperature of the central part of a planet growing in the manner imagined? Conden-

sation of the aggregated mass itself, radioactivity, and chemical reaction within its substance. While each of these agencies is capable of evolving heat, an appreciable rise of temperature of the body within which it acts depends on the rate at which heat is evolved and the rate at which it is diffused through the body and passes away into surrounding space.

While it may be interesting to estimate quantitatively the possibilities of these several activities under certain assumptions, the vital elements in the computations are the assumptions, and as these are the major variables the possible quantitative results must be in the nature of continuous series, the extremes of which may be determinable, perhaps, but the actual case of the planet is sure to be at some indeterminable locus within the intricate complex of these highly expanded series of possibilities.

While the possible temperature produced within the earth by condensation at the center after it had reached its present size may be computed, and under certain extreme assumptions found to be as much 20,000° C., according to Lunn,[8] it must be remembered that compression and condensation began at the beginning of the planet's growth, producing their share of the total possible heat, and that diffusion and radiation into space were taking place at the same time according to their respective rates, to us unknown. Moreover, one of the assumptions on which such high temperatures are based, was that the greater density of the central portion of the globe resulted from the condensation of matter that was supposed to have had formerly the same density as the rocks of the lithosphere, an assumption which appears to

[8] Lunn, A. C. Carnegie Institution of Washington, Publ. 107, 1909, 190.

be highly improbable. How much heat remains to increase the temperature of the growing body depends primarily on the rate of aggregation, or growth, of the planet, also absolutely unknown. Any quantitative statement of the possible amount of heat stored up in this manner within the planet is purely conjectural, and may be any amount between 0° and an amount far less than 20,000° C.

As to the heat of radiant energy that might have been generated by radioactive substances, like radium and thorium, through countless ages of the earth's growth, the field of speculation is limitless at the present time. Interesting speculations have been indulged in by Joly, Strutt, Rutherford, Holmes, and others on the basis of observations already made on the distribution of radioactive substances in rocks and waters on the surface of the globe.[9] Since these observations are based on the effects of radiant energy on other substances, and not on the radioactive substances themselves, the quantities of which are infinitesimally small in comparison with the substances with which they are associated—the average amount in rocks is little more than a million-millionth part—there are possibilities of differences of interpretation of such data in the future progress of investigations in this field of research. What is measured is the effect on an electroscope of air that has been ionized by the emanations of radioactive substances.

Joly considered it probable that radium exists throughout the earth, and estimated the possible rise in temperature of the globe if radium were disseminated through

[9] Joly, J. *Radioactivity and Geology,* London, 1909. Strutt, R. J., Proc. Roy. Soc., A. 77, 1906, 472; 1905, 150. Rutherford, E., *Radioactive Substances and their Radiations,* New York, 1913. Holmes, A., *The Age of the Earth,* New York, 1913.

it in amounts comparable with those in ocean waters. But it has been found that the amount of radium and thorium estimated to be present in rocks, which have been investigated for radioactivity, is considerably greater than is present in sea water, from which data Rutherford has calculated the possible amount of heat evolved under different conditions. He concludes that if a quantity of rock whose specific heat is 0.2 were thermally insulated so that none of the heat generated within it was lost, its temperature would rise at a rate of about 35° C. in one million years. Further, if radium were uniformly distributed throughout the earth in the same proportion to other constituents as in the surface rocks, the heat generated would be about two hundred times greater than the amount of heat lost by conduction. The earth would be getting steadily hotter. Holmes estimates that under the assumption that radium and thorium are uniformly disseminated through the earth in the same amounts as in the surface rocks, enough heat would be generated in one thousand million years to raise its temperature to about 40,000° C. Therefore, it is probable, as Strutt has suggested, that radioactive matter must be confined or concentrated in the outer zone of the earth. If the concentration is the same as that in the surface rocks, and if the observed average gradient of temperature within the lithosphere is to be maintained uniformly, the estimated depth of the zone in question is only twenty kilometers, or about twelve miles.

However, it has been found that the more siliceous rocks contain more radioactive ingredients than intermediate rocks, and still more than rocks low in silica, the mean values being 2.63×10^{-12}; 1.28×10^{-12}, and 0.66×10^{-12} of a gram per gram of rock. From this it is

inferred that the central portion of the earth is almost free from radioactive elements. Holmes suggests that the depth of the radioactive zone may be about thirty miles, and that the temperature due to radioactivity would be about 750° C. at this depth. He considers it probable that the average content of radioactive matter in this zone is somewhat lower than that of the surface rocks.

The apparent value of these estimates is somewhat impaired when one considers that the presence of unusual quantities of radioactive matter, as in the mines at Joachimthal, Bohemia, has not produced a proportionate rise in temperature in the surrounding rocks and region, although local increase in temperature is a common phenomenon in the vicinity of coal beds, and of oil-bearing strata. It would seem as though the knowledge of radioactive substances and of their behavior and distribution is not complete enough to warrant the quantitative deductions already attempted. It is to be noted that volcanic rocks do not contain any greater amount of radioactive matter than other rocks investigated, so that there can not be any question of the possible local heating of igneous magmas by this means, as has been suggested by some geologists.

The possible heat of chemical reactions has been appealed to as a source of high temperatures within the earth, assuming that certain reactions take place, such as oxidation, and the transformation of lighter into denser compounds. But it is necessary to postulate chemical reactions of whose existence, or operation, within the earth we have no definite knowledge; and further to assume such a rate of transformation that the heat evolved may accumulate. Whereas, if such

processes have taken place, their rate may have been extremely slow, and the heat dissipated.

Each of the three processes mentioned, condensation, radioactivity, and chemical reaction, under favorable circumstances might alone produce more heat than is required to account for the observed temperatures in the earth. It is probable that all three processes have operated conjointly to produce the temperatures observed, but the relative importance of their individual rôles is entirely unknown. Undoubtedly the controlling factor in the general problem is the time occupied, that is, the rate of action. Whatever the amount of heat evolved in any period of the planet's growth, or the maximum temperature attained within the central mass, it has been enough to produce molten magmas at some depth below the earth's surface, and beneath all regions in which igneous rocks occur, that is, everywhere that observations are possible.

As to the depth at which temperatures sufficient to produce molten magmas exist, opinions must differ according to the assumed gradient of increasing temperature downward in the earth, and the possible influence of pressure on the melting points of such magmas. For a gradient of 1° C. per one hundred feet a temperature of 1000° C. would occur at about twenty miles, where the pressure would be about 8,250 atmospheres. If the gradient were 1° C. in fifty feet, the depth for 1000° C. would be ten miles, and the pressure something over 4,000 atmospheres. As to the effect of such pressures on melting points of rock magmas and their viscosities, it can be said that they will probably be increased above what they are at atmospheric pressures, but to what extent is at present unknown.

Since there is no direct evidence of extremely high

temperatures in the central parts of the earth, and the pressure increases rapidly until it is about three million atmospheres at the center of the planet, and the whole mass behaves as a rigid, elastic body, it is possible, according to the accretionary hypotheses, that excessive pressures may have obtained within the central mass before it ever became hot enough to be melted under the pressures eventually attained.

Whether the central portion was sufficiently heated when pressures were not too great to permit slow molecular changes of a chemical and crystallizing character is a matter for speculation. A process of metamorphism without liquefaction is conceivable, whereby the central mass may have become crystalline. The conception is probably more reasonable than that it should assume the character of solid amorphous glass, which is within the possibilities of the hypothesis.

If the central portion of the planet consists of denser materials, probably in large part metals, its heat conductivity should be greater than outer portions composed of greater amounts of silicates; so that the heat of the interior should be more uniformly disseminated than in the exterior portion, and the temperature of the interior may be nearly uniform. For the outer zone of incoherent matter, having a much lower conductivity than the coherent inner portion, must have acted as a blanket to prevent its escape. According to Chamberlin, when the earth had attained about one-tenth its present mass, with a radius of about 2,100 miles, it might have had a slight atmosphere of water vapor, carbon-dioxide, nitrogen, and possibly oxygen.[10] At this stage of growth the outer zone should become more coherent through

[10] Chamberlin, F. C., and Salisbury, R. D. *Geology,* vol. II, New York, 1906, 93.

cementation and the formation of new chemical compounds; and when the atmosphere attained sufficient density to permit the existence of water in contact with it, water would permeate the incoherent zone of constantly falling matter. However, its amount should not be enough to form bodies of water upon the surface, since the relative volume of present oceans to the solid earth is only about 1: 765,840, and the depth of the once incoherent material we may imagine to have been still very great.

Whether bodies of water would occur on the earth's surface before the completion of the accretion of nebulous matter from surrounding space under this hypothesis would depend on the rate of infall, which should be an increasing quantity with growing planetary mass, until the supply of material became reduced. It would depend also on the depth of incoherent matter, and on the rate at which it would become coherent under atmospheric influences. We may imagine the outer zone of the earth, as it approaches the end of its more rapid accretionary growth, to consist of the latest fallen matter, somewhat heterogeneous in constitution, quite incoherent in the outermost portion; and becoming more and more coherent downward to where it was compressed by the overlying weight and was cemented by permeating waters; the outer surface possibly pitted like the moon.

The chemical status of the matter in the outer portion of the planet, from the time it was large enough to maintain an atmosphere, and when water became a liquid constituent, must have been quite different from that of the innermost portion during the period of its accretion. Chemical reactions should be more active at higher temperatures, and higher temperatures might obtain on account of the heated center of the planet, and the

greater force of impact upon the fall of larger masses. Crystallization would probably accompany condensation, and a coherent crystalline mass result, the early stage of the present lithosphere. Its composition should be about the same as that of the average of igneous rocks, but more or less heterogeneous according to the composition of the nebular aggregations that formed it.

As already said, however evolved, there has been developed heat enough to produce volcanic lavas that are molten at about 1000° to 1500° C. Whether the earth's temperature is much more than enough to render magmas mobile is a question that can only be answered by evidence that rock magmas have been superheated above their melting points, and have been capable of melting solid rocks which were at much lower temperatures than the molten magmas.

Whether the temperature of the planet has ever been much higher than it is at present is a matter which may be determined by evidence that there has been considerable cooling and contraction since the lithosphere assumed its present petrographical character. However, since condensation may result from molecular readjustment under great pressure, evidences of contraction within the planet do not necessarily demonstrate a cooling sphere. Diffusion of heat into space is clearly indicated by the temperature gradient beneath the surface of the earth, but with the chemical and physical means of evolving heat from the material substance of the earth, it remains a question whether the heat lost is greater than that evolved within the planet.

The warping and dislocation of the lithosphere clearly testify to a shrinking globe, and it is in order at this time to consider the possible results of the contraction of a planet formed in the manner just imagined. If the

globe were homogeneous and the contraction uniform in all parts, the volume would decrease without effecting any change in its shape, or any internal shear. If the globe were heterogeneous in substance, and the contraction not uniformly distributed, shearing and deformation would result. Contraction due directly or indirectly to pressure should be greatest in the central portion. Contraction due to cooling should be greatest where the rate of cooling is greatest, that is, where the temperature gradient is steepest, somewhere in the outer portion of the planet. It is possible that molecular readjustments may be taking place gradually throughout the interior of the planet, and the resulting contraction may be distributed throughout the interior of the globe. The outer zone, or lithosphere, may be contracting at a much lower rate, or may be actually gaining in volume through chemical reactions, such as hydration.

Chamberlin has estimated that a shrinkage of 1 per cent of the volume of the earth would be sufficient to account for all the apparent folding and overthrusting that has taken place since the beginning of Paleozoic times. W. H. Emmons has calculated the volumetric change in average rock with a coefficient of expansion of 0.0000199 to be 0.0006708 for 1° C., or about 1 per cent for 15° C. If the rate of cooling in previous ages were the same as the present rate, which has been estimated to be 0.00000045° C. annually, the time required to shrink 1 per cent through cooling alone would be about 33,000,000 years. Such calculations as these are far from determinative of anything but an approximate order of magnitude, and in this case indicate that the combined causes of condensation within the globe already mentioned are competent to produce the deformation

that appears to have taken place in the lithosphere since the beginning of the Paleozoic era.

Heterogeneity of substance, differences of composition and of density within large masses of the planet, should occasion differences in the rates and amounts of volumetric contraction in various parts of the globe, resulting in shearing stresses within the elastic rigid mass. The resultant motions in such a spherical system of stresses must be chiefly in the direction of radii of the sphere, that is, the major differential movements within the central mass of the earth must be in the nature of depressions, or radial shortenings, which must communicate themselves to the outward portion of the lithosphere and find expression in the warping, folding, and dislocation already described. The adjustment of the lithosphere to the shrinking core remains to be considered.

As already shown, the strength of mineral crystals and rocks is not enough to support their own weight when their aggregated mass passes certain limits. The curvature of the earth's surface is so slight that, as Woodward has estimated, the strength of the lithosphere would have to be from 500 to 1,000 times greater than the crushing strength of granite, in order that it should support itself as an arch. Consequently, when any portion of the earth's interior contracts, the overlying lithosphere must sink; and, since the surface portion of the lithosphere does not contract at the same rate as the interior, it must buckle up as it settles.

Since elastic bodies, such as rocks, behave more nearly like ideal rigid ones the less stress they sustain, and behave more like plastic ones when under stresses that are near their limits of elasticity, sustaining permanent shear when the stresses exceed these limits, the outer-

most portions of the lithosphere will act with apparently greater rigidity than deeper portions. In places, for short distances, they may act as solid arches, or as struts, withstanding longitudinal compression. In places they may crack apart under tensional stress, or under torsion, or a shear.

Fractured blocks of any size will behave as rigid bodies to a depth within the earth at which the superincumbent weight just equals their crushing strength when unsupported laterally. Below this depth they may still exist as rigid blocks, provided the lateral support from adjacent ones compensates the overlying weight to such an extent that the difference in stresses is within the limit of elasticity, or coherence, of the rocks composing the blocks. It is the deep-seated contraction and shearing that has undoubtedly produced the profound displacements that result in more or less vertical faults in places grading into flexures, as in the high plateaux of Utah and elsewhere, as described by Gilbert, Dutton, and others, who, with Suess, consider them the more profound movements in the lithosphere, frequently being accompanied by volcanic eruptions.

Turning to those theories of the formation of the earth that postulate the cooling of a gaseous and liquid sphere, it is to be noted that various assumptions as to the present condition of the planet's interior have been made, and are still advocated by some geologists. There are those who assume that the earth's interior is still molten with a crust of solid rock forming the lithosphere. This hypothesis disregards the astronomical demands for a rigidity like that of steel, and fails to account for the major demands of isostasy as expressed by the occurrence of oceans and continents; and since the density of rocks is known to be greater than the

density of their molten lavas, the advocates of such a hypothesis are driven to assume that the molten magma beneath the lithosphere is denser than the overlying rocks, and consequently must have a different composition; that the magmas erupted from this universal reservoir have a different composition from those that reach the upper portion of the lithosphere and appear on its surface as volcanic lavas; and that their composition is changed en route by dissolving quantities of the rocks through which they flow; not the rocks they are found in contact with after solidification, but deeper bodies previously encountered. This hypothesis assumes highly superheated magmas capable of imparting sufficient heat to melt vast quantities of solid rock without chilling the intruding magmas, and of producing modes of intrusion into solid rocks which will be discussed in another place.

According to those hypotheses that postulate a solid core within the earth, it is assumed that crystallization of minerals has taken place from the liquid globe in consequence of excessive pressure, which is supposed to have raised the crystallizing points, or points of saturation, within the magma solution. It is assumed that the denser minerals concentrated at the center of the earth, and that differences in composition and in density within different parts of the planet may have resulted from convection currents, as well as from differential crystallization. It is to be noted that convection currents may be imagined only where fluidity and differences in density are sufficient to produce them, chiefly in the outer portion of such a liquid sphere.

Modifications of this hypothesis assume, in one case, that there is a zone of liquid magma between the inner core and the outer shell or crust; in another case, that

the whole earth is solid with the exception of residual lakes of magma not yet solidified; in still another case, that magma lakes or basins are ephemeral, being produced by local accessions of heat, or by relief of pressure through dynamical changes in the overlying lithosphere. In these hypotheses the heat within the earth is assumed to have been derived chiefly from the former liquid globe, the principal cause for shrinkage of volume being due to cooling of a once highly heated planet. The possible temperature of the earth under these hypotheses is generally estimated on the basis of some assumed temperature of a liquid earth, and a particular rate of cooling, to conform to the estimated gradient of temperature from the present surface inward, the resultant distribution of temperatures having been calculated by Lord Kelvin. These hypotheses have been suggested to meet the demands of rigidity, and the difficulties of having a lithosphere of matter denser than the molten magma formerly supposed to underlie it.

Quite a different form of hypothesis is based on the assumption that the increment of heat observed near the surface of the earth continues at nearly the same rate four thousand times farther to the center of the earth. It would be above the critical temperature of all known substances within the earth, so that these must be in gaseous phases, but under the enormous pressures that exist at the center of the earth it is assumed that these gases would possess the rigidity which the earth appears to have. This rigid, amorphous, solid gas is the central body of the earth according to the hypothesis of Arrhenius.[11]

It would seem that if this substance retains the prop-

[11] Arrhenius, S. A. *Zur physik des Vulkanismus, Geol. Fören. Förhandl,* 22, 1900, 395.

erties of gas, as its name implies, it should yield to changes of stress, which, under the attraction of the moon, tend to produce tidal deformation within the planet, and which, according to the calculation of Sir George Darwin, are eight times as effective at the center of the earth as at its surface. If the substance of the earth under this hypothesis is an elastic amorphous solid with the rigidity of steel, it would seem to be no more a gas than plate glass is a liquid with its rigidity. Neither substance is crystallized matter, but both are solids in the ordinary sense of the word. The hypothetical "solid gas" would seem to have the characteristics of glass, rigidity, elasticity, and an amorphous molecular constitution. The difficulty of creating heterogeneity in a mass derived by the compression of a mixture of superheated gases as well as its apparent resistance to external distractions would seem to be fundamental objections to such a hypothesis. There is also the improbability of the existence of the high temperatures assumed.

In whatever manner it may have been formed, an earth possessing the characters best understood by means of the accretionary hypothesis satisfies for the present the requirements of the physical features of the lithosphere as now known: profound displacements through the shearing of a heterogeneous elastic mass, yielding at irregular intervals to accumulated strains, now in one place, now in another, as readjusted portions reach their limit of resistance to the constant pressure of overlying weight, and unequal contractions shift the resultant stress. Upon this slowly shrinking core the enveloping zone of rock settles closely, its lowest portion yielding like a plastic substance to the changing positions

of the inner mass; its upper portion as it is nearer and nearer the surface behaving more and more as a rigid, brittle body, extremely heterogeneous because of the various kinds of rocks and their manifold distribution and arrangement in it. The larger accommodations show themselves as vast depressions and relative elevations of great areas of the lithosphere, ocean basins and continental plateaux of slightly warped sediments, the so-called "horsts," such as the Indian peninsula and the greater part of Africa, according to Suess.[12]

The subsidence of rigid blocks of great extent is accompanied by warping on a great scale, together with the crowding or thrusting together of the edges of adjacent blocks in some instances. Warping or flexure bends the lithosphere, in places downward in synclinal curves, in places upward in anticlinal arches, some broad and slightly curved, others comparatively narrow and abrupt; in some places with parallel axes like successive waves; in others with divergent axes like an irregularly warped plane which has experienced torsional stress. These appear to be the fundamental movements which provide the basal elements of all the problems of tectonic structure and of volcanic intrusion within the visible parts of the lithosphere.

The bending is accompanied by fracture and faulting, probably in all instances, some fractures being so minute and close together as to be overlooked; others, large enough to command recognition; while some are of great dimensions, being traceable for many miles of length and representing displacements of thousands of feet. The extent of territory sometimes affected by warping is indicated in part by the magnitude of great earthquakes,

[12] Suess, E. *The Face of the Earth,* vol. II, London, 1906, 254.

which follow the rupture and displacement of portions of the lithosphere. The Assam earthquake of 1897, according to Oldham, was accompanied by the displacement of 10,000 square miles of country along a thrust plane, and was considered by Milne to have originated from a relief of strain over an area of 500,000 square miles.[13]

Fractures commonly occur in groups or systems, some approximately parallel. Perhaps the greatest system of nearly parallel fractures is that in East Africa extending through the Great Rift Valley northward into Syria. These fractures appear to have occurred in vast horsts as though from tensile stress, for long narrow blocks between the major fractures have settled down with step-faults on both sides of the trough-like depression, as in the Rift Valley of the Great African Lakes, and the minor valley of the Dead Sea. A trough-like depression where the faulting is along one side, an inclined trough, is to be found in Death Valley, Southern California.[14]

A system of curved, more or less concentric, fractures and faults may be produced by a dome-like arching, and when the center sinks a caldron-like depression results, surrounded by step-faults. Such caldron-like subsidence has taken place along the west coast of Italy and elsewhere in the Mediterranean region, according to Suess, and appears to be actively taking place in the vicinity of the Æolian Isles, judging by the frequency and the location of violent earthquakes.[15] A striking example of circular subsidence may be found in Crater Lake, Oregon, described by Diller, where the upper portion

[13] Milne, J. Proc. Roy. Soc. London, 1906, 369.
[14] Ball, S. H. U. S. Geol. Survey, Bull. 308, Washington, 1907, 210.
[15] Suess, E. *The Face of the Earth,* vol. IV, 581.

of a great volcano has disappeared apparently by subsidence within its conduit.[16]

Fractures that result from the torsion of a rigid plate, as shown by Daubrée, form a divergent group radiating from the place of maximum resistance. Similar fan-like systems of fractures and faults occur on large and small scales. Those on a large scale may be accompanied by more or less folding of the fractured blocks in the form of ridges and mountain ranges, such as the radial systems surrounding the complex of the Swiss Alps. A fan-like group of minor fractures occurs in the upturned base of Electric Peak in the Yellowstone Park.[17]

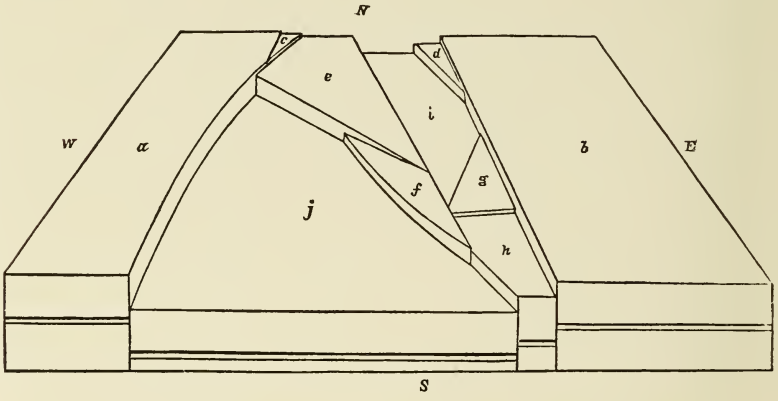

Fig. 49. Stereogram of the Musinia block-faulting

J. W. Powell

Besides the groups of dominant fractures which have been mentioned there are subsidiary ones that may belong to the same system and be contemporaneous in

[16] Diller, J. S., and Patton, H. B. U. S. Geol. Survey, P. P. 3, Washington, 1902.

[17] Iddings, J. P. U. S. Geol. Survey, 12th Ann. Rep., 1890-1891, part 1, 569.

FIG. 50. FRACTURED LIMESTONE WITH SEAMS OF CALCITE

C. D. Walcott, U. S. Geol. Surv.

origin, but may intersect the major faults abruptly, crossing them almost at right angles. Such fractures may be illustrated by the system described by Gilbert and Powell in the Musinia zone of diverse displacement near the southwest edge of the Wahsatch Plateau in southern Utah,[18] shown by stereogram in Figure 49, and by the fractures produced by torsion in some limestone which may be seamed with calcite as in Figure 50. However, it should be noted that the fractures in any system are not necessarily formed at one moment, if indeed a single fracture may be so formed. A rock fracture probably creeps gradually through a block as one part after another reaches the breaking strain, and various fractures in a complex system may succeed one another in a more or less interrupted series, as block after block gives way. Undoubtedly displacements along fault fractures, some of which amount to thousands of feet, have progressed gradually, though it may be at irregular intervals, not uninterruptedly.

Later systems of fractures may be imposed upon blocks already traversed by an earlier system, owing to subsequent rupture under a different set of stresses. They may be of the same order of magnitude, or of very different orders, as when a mountain range composed of closely fractured strata is intersected by profound faults. The thrusting together of portions of the lithosphere results in foldings, shearings, and overthrusting that may pile up mountain ranges like the Appalachians and the Alps.

The relation between fracturing and volcanic eruption and intrusion is obvious. Fractures are the lines of least resistance followed by flowing lavas. However,

[18] Powell, J. W. U. S. Geol. Geogr. Survey, Rocky Mountains, Geol. Ninta Mountains, 1876, 16.

there are fractures that do not offer any opportunity for the passage of lavas, since they occur between blocks that are thrust so tightly together that there is as much resistance along the fractures as in the unbroken rocks. All fractures are not available for intrusions. Some may be opened by magmatic intrusion, others not. Volcanic eruptions have taken place frequently in regions of profound block faulting; but they have seldom, if ever, occurred in those parts of a region that were undergoing great compression, complex folding, and overthrusting.

In conclusion it may be said, that it is highly probable that profound displacement and warping of the lithosphere result from contraction of the central portion of the planet, due, in part, to molecular rearrangement through crystallizations and chemical readjustments; in part, possibly, to loss of heat; that these changes may be acting continuously throughout the interior of the earth, but not necessarily at uniform rates in all parts of it, owing to heterogeneity of material, and to differences of pressures at different depths; irregularities of warping and of fracture within the lithosphere depending upon the heterogeneity of its material, and on the disposition of planes of weakness or of previous fracture within it, and on the ability of portions to sustain prolonged stresses. It appears to be quite possible that the temperature of the interior of the earth is not greater than that of the hottest volcanic lavas at its surface, from 1000° to 1500° C. Temperatures higher than these are purely hypothetical.

CHAPTER VI

THE EXTRAVASATION OF MOLTEN MAGMA

The extravasation, or eruption, of molten magma from its position of rest, or its "magma basin," into new positions among solid rocks of the lithosphere, or upon the surface of the earth, is the fundamental element in the problem of volcanism, for an intelligent discussion of which the preceding chapters have been a necessary introduction. The subject may be treated under the following heads:

1. The source of rock magmas in any one region.
2. The cause of their extravasation or eruption.
3. The process by which they have been intruded among rocks of the lithosphere, or have been extruded upon the earth's surface.
4. The resulting bodies of igneous rocks.

These divisions of the subject, however, can not be discussed wholly independent of one another, so that some repetition or blending of the discussion is to be expected.

The Source of Rock Magmas

In attempting to locate the source of molten magmas, it is necessary to harmonize certain facts which seem to be established with reference to the earth as a whole and rock magmas in particular. They are as follows:

Rock magmas are erupted in conjunction with profound dislocations of the lithosphere, and appear to rise

from deep within the earth, but this statement does not apply to some local or comparatively small outbursts of lava at the earth's surface whose mode of eruption will be discussed later on.

The chemical composition of magmas is such that they appear to have come from depths below any at which sedimentary strata exist.

Their general similarity in composition throughout vast tracts of the earth indicates that the "basins" from which they flow contain much the same kinds of magma, at least for regions of great extent.

The recurrence of eruptions of similar magmas in one region after long intervals of time, in geologically different epochs, indicates that magmas of like composition may be erupted from the same general source at widely remote periods, and that there is no basis for the old theory of von Waltershausen and others that a crust is solidifying over a molten globe composed of concentric zones of magma varying in composition and density downward, and that modern lavas are on the average less siliceous, more basaltic, and from deeper zones than very ancient ones, which were supposed to be more siliceous and mostly granitic in composition.

However, the differences between the rocks of some petrographical provinces, already noted in a previous lecture, show that there are some quantitative differences between certain great "magma basins."

The universal occurrence of volcanic action in all parts of the earth, where dynamical movements of the lithosphere were favorable, indicates the universal existence of magma deep within the lithosphere, or beneath it.

The widespread occurrence of volcanic activity at various times and the molten condition of the lavas

erupted show the widespread occurrence within the earth of temperatures sufficient to produce liquefaction.

The length of time through which volcanic activities have taken place in any one region, and the extension of these activities throughout geological history, indicates the continuance and diffusion of internal heat throughout the earth, and militates against the idea that the heat of volcanism may be a local evolution dependent on special dynamical or chemical actions.

These are some of the facts that should be borne in mind in a discussion of the possible source of molten magma. The probability that the interior of the earth consists of mineral matter having melting points nearly the same as those of the mineral components of rock magmas, and the further probability that whatever heat exists in outer parts of the earth is present to the same or even higher degrees deep within it, render it equally probable that such material would be as molten as rock magmas throughout the earth's interior unless some agency counteracts the normal effect of heat.

Pressure is known to operate in the opposite manner to heating, but in a very different degree within the range of laboratory experiments. However, within the earth there are pressures far beyond those yet experimented with, so that the conclusion seems inevitable that if material capable of becoming liquid at 1500° C. exists within the earth and the earth behaves as though it were as rigid as steel, either the temperature is not as high as 1500° C., or its liquidizing effect is offset by that of excessive pressures, which may possibly produce crystallization of highly heated matter.

High pressures exist within the earth; high temperatures are problematical. Temperatures of 1000° to 1500° C. certainly exist almost universally in regions

from which volcanic lavas flow. How much higher temperatures may obtain in those places in which magma existed before it began to be erupted we have no means of finding out. We only know that magma appears to come from a region where toward the attraction of the moon the earth behaves like rigid steel, and that it flows from a volcanic crater with a liquidity comparable with that of water. Whence this apparent change of behavior?

The physical characteristic which seems to have changed with shifting position is the viscosity of the magma, one of the principal factors in the problem of the eruption, intrusion, and outflow of volcanic lavas. Is it possible that magmas exist at considerable depths as exceedingly viscous bodies, and become more liquid as they approach the surface of the earth? Let us review briefly the agencies affecting viscosity or liquidity of solutions like rock magmas. Heating increases liquidity, but it is not likely that magmas would become hotter as they pass from their source to the surface of the earth, except quite near the surface, where they may be capable of developing an appreciable amount of heat within themselves through the chemical combination of gases which may become active when liberated from other combinations. The earth is undoubtedly cooler outward, and as magmas pass upward they should lose heat in proportion as the wall rock is cooler than the lava, consequently their viscosity should increase, not lessen, so far as their change of temperature is concerned, and this is the case in certain instances which will be considered more fully in another connection. Isostatic pressure affects viscosity, especially very high pressures. It is known that gasoline, for example, under 20,000 atmospheres at ordinary temperatures, becomes

about as viscous as vaseline,[1] and wax becomes a rigid body, but of the specific effect of high pressures on rock magmas we have no information. They should render them more viscous, and relief of pressure during magmatic eruption should render them less viscous.

Pressure may affect viscosity indirectly by producing combinations of gaseous constituents with other chemical constituents at high pressures, thereby fixing the gaseous constituents and reducing their effect upon the liquidity of magmas. However, it is to be noted that such compounds, like hydrated ones, have a lower fusion point than analogous compounds free from what may be called gaseous components. It is possible that with lessened pressure such compounds may become unstable, and upon breaking up into other compounds may liberate the gaseous components which may then behave as dissolved gases in the magma, and may still further increase its liquidity. The rôle of gases in magmas will be discussed more fully in connection with the causes of eruption. Accession of gases to magmas should increase their liquidity, and it is to be expected that gases will be absorbed by magmas as they pass through wall rocks. It is to be noted that water is more abundant in the uppermost rocks of the lithosphere than in deeper ones.

While these factors have very different degrees of effect on the viscosity of magmas, it must be remembered that they operate at very different rates during the eruption of magmas. Thus, slow intrusion through cold rocks may chill a magma and greatly heighten its viscosity; but a rapid rise through a hot volcanic conduit may produce very little change in temperature, although very sudden change in pressure. Slight

[1] Bridgman. Proc. Am. Acad. Arts and Sci., 47, 1911, 337; and Johnston, J., and Adams, L. H., Am. Jour. Sci., 35, 1913, 1.

accession of hot aqueous gas may increase liquidity, but too copious influx of water gas at a moderate temperature may chill a magma and render it highly viscous. With these conditions in mind, we may imagine the source of igneous magmas to be located deep within the lithosphere, more properly at its lower limit, if by lithosphere we mean the outer portion of the planet which consists of rocks having the physical properties of the crystalline rocks that are exposed at the earth's surface.

The rate of transmission of earthquake waves, according to Milne,[2] indicates that thirty miles is about the maximum depth at which the substance of the earth behaves like rock having the elasticity and rigidity of that at the earth's surface; and it also indicates that below this limit the materials of the outer zone appear to merge rapidly into a nucleus with still higher rigidity, perhaps twice as rigid as steel. With such a conception of the relative rigidity and elasticity of the outermost zone and the interior of the earth, the term "crust" becomes distinctly inappropriate and misleading, and should be discarded. It is to be noted, however, that much more data concerning the transmission of earthquake waves are needed in order to establish definite limits to the lithosphere, or determine the degree of homogeneity of the inner portion of the earth.

What may be the physical character of the lowest portion of the lithosphere where it ceases to be like crystalline rocks? Brittle and elastic within known limits at the surface of the earth, it may be thought of as becoming somewhat less brittle under increasing load and rising temperature, until the minerals with lowest

[2] Milne, J. Proc. Roy. Soc., London, 1906, 369.

melting points under existing pressures pass into amorphous compounds. The temperature necessary to produce transitions from crystalline to amorphous phases must depend on the crystallized substance, the pressure, and the gaseous or liquid matter associated with it, which may combine with it to make an amorphous solution. At higher temperatures more kinds of mineral crystals should pass into an amorphous phase, and blend with the amorphous matter already present. The viscosity of any amorphous substance at its transition temperature depends on its chemical composition and on the pressure. It is known that some of the more siliceous and more aluminous mineral compounds are highly viscous at transition temperatures.

At sufficiently high temperatures, pressure permitting, it is possible for the material below the lithosphere to be wholly amorphous and highly viscous; but it is also possible that pressure effects may exceed temperature effects, and that a crystalline mass, stable only under the existing pressure, may continue the lithosphere downward into the zone of high temperatures, if the term lithosphere were defined as a crystalline body. However, obsidian glass is rock, and is in places a component part of the lithosphere at the earth's surface; hence there may be a doubt as to a proper definition of the term lithosphere. It may be best to include within the term all of the outer zone of the earth which may have the chemical composition of rocks, whether crystallized as at the surface of the earth, or more or less amorphous and rigid like cold glass, or possibly equally rigid because of high pressure although hot. It does not appear to be possible that there should be any zone of liquid substance beneath the lithosphere, for any considerable

volume of liquid, whatever its density, would permit noticeable tidal distortion in the overlying rigid zone.

It is possible, then, that there may be a zone at the base of the lithosphere consisting of material capable of fluid motion wherever there may be any change of stress due to shifting of overlying load through warping, and that this zone or base may consist of amorphous material; or of crystallized minerals in such a state of equilibrium that they may pass into solution in one another upon the requisite change of pressure; or it may consist of a mixture of such crystals and amorphous substance, for in the nature of the case there should be very gradual transitions in all the physical characteristics of different parts of the earth's interior, and no abrupt changes. Pressure increases gradually downward. Heat must be generally diffused, and transitions between deep portions having different temperatures must be very gradual. Differences in chemical and mineral composition of contiguous deep-seated portions of the earth are probably comparatively slight, and transitions in composition gradual. So that what may be called the base of the lithosphere probably has nearly the same temperature, pressure, composition, and density as the material just above it, and as that immediately below it. It is in such a zone that we may imagine the lowest source of molten magmas to be located. A primitive "magma basin," then, is not a vessel of liquid, but a condition of the earth, obtaining possibly at various unknown distances below the surface, according to circumstances of composition, temperature, and pressure.

There seems to be no basis for the suggestion that molten magma rises from the central parts of the earth by a process described as kneading, under the rhythmic

action of an elastic body struggling with incipient periodic tides, and that the material dissolves its way by selection of more soluble or fusible material in the heterogeneous aggregation postulated by the accretionary hypothesis.[3] The fusibility and liquidity of iron as compared with many silicates militates against this suggestion; and the evident relationship between occasional profound dislocations and volcanic eruptions militates against the idea that magma works its way up through thread-like pipes as chance may furnish more solvent materials.

The Cause of Magmatic Eruption

Why do molten magmas shift their position and rise through the lithosphere? The occurrence of volcanic eruptions in regions of profound displacement, along lines of trough-like dislocation, as in the Great Rift Valley in East Africa, and on the sides of synclinal flexures, as in the Cordilleras of the Pacific Coast of North and South America, indicates that the fracturing of the brittle lithosphere, in adjusting itself to a shrinking core, was the occasion for the displacement of the potentially mobile, rigid magma zone beneath the frangible zone of rock. This adjustment undoubtedly produced the shifting of the more plastic material, which should move from places of higher pressures or thrusts to places of less pressure, which should exist beneath those parts of the lithosphere that experience tensile stresses due to the stretching of the under portions of stiff synclinal flexures, or where tangential thrusting may induce incipient arching of the more rigid portion of the overlying lithosphere.

[3] Chamberlin, T. C., and Salisbury, R. D. *Geology*, vol. II, 1906, 103.

The effect of tension in that part of a heavily weighted system that is loaded beyond its limit of elasticity is to stretch the mass, or to produce a shear or flow in the direction of the pull, that is, to thin it in this place, allowing the more mobile underlying mass to rise against it. Where the limit of cohesion is reached and fracture is possible, the more mobile mass may insinuate itself between the parting sides.

In the basal zone we have imagined that any relief of pressure, such as tensile stress, would tend to render the pseudo-rigid, amorphous material less viscous; when the pressure is sufficiently reduced it may become mobile. It is to be remembered that distinctions between rigidity, with frangibility, and plasticity, with highly viscous movement are dependent on the magnitude of stresses and the time during which they act. A highly viscous substance may offer very great resistance to sudden or rapid shearing, and may fracture; although it may yield to a small shearing stress in the course of a sufficiently long time, and may flow without rupture. Consequently, there can not be any definite boundary between the lower portion of the lithosphere which may be considered to be pseudo-rigid, but may fracture under a sudden shearing stress, and that portion which may be as stable and rigid as rocks near the surface of the earth. The transition between them must be gradual, and the operation of initial flow of magma here suggested should be equally indefinite and ill-defined in its boundaries.

The density of the more movable magma should be almost the same as that of the material just above it, and its viscosity almost the same. That portion which shifts its position upward because it experiences a little less pressure in this direction, at the same time should

experience whatever physical changes diminished pressure permits; namely, a slight expansion of volume, slight diminution of density and of viscosity, and whatever changes in chemical equilibrium may accompany relief of pressure, according to their respective rates. With protracted uprising and continued relief of pressure there should be further increase in volume and diminution in density and viscosity, with eventual liberation of gases from chemical combinations, and consequent decrease in viscosity.

The rising magma at first should encounter walls having almost the same temperature as its own, and the loss of heat by diffusion, taking place with extreme slowness, should be almost imperceptible, and negligible at a very short distance within the moving mass. This relationship between temperatures of magma and wall matter may continue for a considerable distance upward, so that changes in the temperature of the magma should be much slighter at first than changes in pressure. The poor heat conductivity of rock magmas should permit the interior of a rising body of magma to retain its initial temperature almost unimpaired for very considerable distances of ascent, especially in the early part of its upward course, and even in later portions within cooler walls, if the rate of flow were at all rapid; very slow ascension with long periods of rest should cause more change in the temperature of the magma.

However, if magma were flowing through previously heated fissures, such as the channels along which volcanic lavas had been flowing for centuries, the loss of temperature might be almost inappreciable, and lava might reach the earth's surface through such channels with nearly the same temperature as that with which it began its ascent. The pressure, on the contrary, should fall

according to the velocity of ascension until it is only that of the atmosphere at the earth's surface, where the lava column finds its equilibrium. The pressure of the lava column on the magma at its base must counterbalance the pressure of its retaining walls of almost the same material. The factor of rigidity in the lithosphere, and possibly the viscosity of the magma itself, must counterbalance the difference in densities of the molten magma and the crystallized wall rocks. It is to be remembered that the rigidity of the lithosphere and the viscosity of magmas are both variable factors; one greatest at the earth's surface, the other greatest at the greatest depth at which molten magmas exist, at which place the rigidity of one and the viscosity of the other are supposed to merge into one another.

A very important factor in the eruption of volcanic lavas is the content of chemical elements that may become gases under favorable conditions, but which may exist in combination with other constituents of magmas and form liquid compounds, or even crystallized compounds, under great pressures. In meteorites, which may be deep-seated portions of exploded planets, sulphur is combined with iron in troilite, FeS; and with calcium in oldhamite, CaS; carbon is combined with iron in cohenite, Fe_3C; chlorine with iron in lawrencite, $FeCl_2$; and phosphorus with iron and nickel in schreibersite $(Fe, Ni)_3P$.[4] It is possible also that some part of these elements may exist in magma solutions under great pressures without being in chemical combination, and may behave as dissolved gases, as they certainly do when near the earth's surface, in volcanic craters, and in lava flows.

[4] Wahl, W. A. *Zeitsch. f. Anorganische Chemie,* 1911.

The point to bear in mind is, that all of the gaseous constituents appearing in lavas near the earth's surface do not necessarily exist as uncombined gases in magmas when under very great pressure. Moreover, part of the gases, notably part of the water gas and presumably of others, such as carbon dioxide and nitrogen, enter magmas from the wall rocks, and one of the great questions in volcanology is, What are the relative amounts of the gases derived from the walls of conduits and of those inherent in magmas before they began to move from their original source?

If there were any gases and any water in wall rocks enclosing molten magmas at the time of igneous intrusion, the heating by the magma would increase the vapor tension in proportion to the temperature of the magma, and since rising temperature increases the viscosity of gases at constant volume, and since molten magmas are capable of dissolving gases, the gases in the wall rocks would find readier egress through the magma, provided its vapor tension, or its vapor concentration, were not too high, than through the heated rocks whose pores, if any, would become smaller as the crystals in the rocks expanded with heating. In some instances the unequal expansion of different kinds of minerals in rocks composed of various minerals, or the unequal expansion of crystals in different directions, might tend to develop or enlarge capillary spaces upon increase of temperature, but this effect should be greatest nearest the intruded magma, aiding escape in this direction.

Absorption of water from wall rocks undoubtedly takes place, but to what extent? It has been estimated that by raising the temperature of an amount of water, which is 5 per cent of the mass of a given magma, from about 93° C. to about 1650° C, enough heat would be

withdrawn from the magma to reduce its temperature by about 305° C.[5] The estimated quantities are well within the possibilities of magmatic action. A temperature of 93° C. may be that of the earth remote from igneous intrusion at a depth of two or three miles, but 5 per cent of water is a large amount to exist within rock masses 10,000 or 15,000 feet below the surface, except in the case of some permeable stratified bodies, like sandstones. If the water content were partly combined with other constituents in mineral compounds, or were inclosed in cavities within crystals, it would not all become available for absorption by a magma in contact with the wall rock. On the other hand, 5 per cent of water within molten magma at 1300° C. would be an energetic explosive when the magma reached a position where the overlying pressure was not much more than one atmosphere.

It is probable that most molten magmas do not contain as much as 5 per cent of water in solution, or in combination in mineral compounds. Certainly, many unaltered igneous rocks when analyzed do not yield 1 per cent, and few rock glasses contain more, though some yield as much as 5 per cent on analysis. Perfectly fresh obsidian from Obsidian Cliff in the Yellowstone National Park, contains about one-half of one per cent of water, and when melted expands into a highly inflated pumice. The obsidian flow at Obsidian Cliff was a quiet outflow, that had a pumiceous upper surface like many other obsidian lavas.

It is to be noted that many outflows of lava, certainly those from the craters of large volcanoes, pass through fissures or conduits that have been heated for centuries,

[5] Chamberlin, T. C., and Salisbury, R. D. *Geology*, vol. I, 1905, 635.

perhaps for thousands of years, by previous eruptions, and that whatever water gas reaches modern lavas has been heated by slow passage through the heated zone encircling the conduit. The previous heating of the small percentage of water that may reach volcanic lavas through wall rocks in such cases has been accomplished by great volumes of heated rocks compared with which the amount of water transmitted is probably a small fraction of 1 per cent. It is possible, nevertheless, that this small percentage of water is a relatively large factor in much that is commonly considered the most essential feature of volcanic activity, its explosive energy.

It has been suggested that the diffusion of gases through magmas while in a conduit may be a potent source of kinetic energy; that they transfer heat from hotter to cooler regions, and that they increase the vapor tension of the parts of a magma in which they may accumulate. The effectiveness of such a process must depend upon the quantity of gases transfused, the rate of transfusion, and the differences in temperature and pressure between various parts of a body of magma. Within the highly compressed, solid core of the earth, it is not to be assumed that there are pores through which gases may flow. Any transference of gases through its compact mass must be by molecular diffusion of the most sluggish type, a much slower process than the diffusion of heat itself by conduction.

It is only in the molten magma that an appreciable amount of migration of gaseous material may be imagined. Occasion for its migration is to be sought in differences of pressure, in part due to load, in part to temperature, affecting vapor tension. Within the zone of rigid, or potentially mobile, magma we have imagined the viscosity to be so high as to approach

rigidity, and the temperature to be nearly uniform, but the pressure necessarily varying with depth and with the stresses in the overlying load. In such a region, it is conceivable that there may be an extremely slow migration of gaseous constituents, if any exist there in an uncombined state, but the quantity transfused and the rate of movement should be extremely small. The liberation of gaseous elements through dissociation of compounds in which they may exist under high pressures should be accompanied by an absorption of heat and a diminution of temperature.

In more mobile portions of rising bodies of magma, as already said, a somewhat greater content of uncombined gases may be present, and slightly increased rates of diffusion should obtain, due chiefly to decreasing pressure in higher parts of the rising body, the temperature differences being less effective, probably. However, when magma is rising through a conduit its rate of flow may be greater than that of gaseous diffusion, but this diffusion is to be added to the magma flow, so that the gases should rise somewhat faster than the magma; in fact, with an accelerated velocity, because changes in temperature would be more rapid the higher the magma rose in the lithosphere, and also because with lessened pressure, gases may separate from solution and expand, at the same time consuming heat and thereby further reducing temperature.

Since the expansion of gases absorbs heat, the ascension of expanding gases into higher portions of a magma body, if not accompanied by chemical reactions that generate heat, should be attended by a reduction of temperature instead of an increase as assumed in some hypotheses. It is well known that the sudden expansion of magmatic gases, when some lavas reach the atmos-

phere, chills the inflated liquid into pumiceous glass. It does not necessarily follow, then, that the diffusion of gases through magma columns within volcanic conduits maintains their temperature. Certainly the accession of gases from wall rocks tends to cool them, so far as the gases remain inert chemically; but there is the possibility that chemical reactions within highly heated mobile lavas under comparatively little pressure may be effective in maintaining temperature, if not in actually augmenting it, for there are abundant evidences that oxidation, which has affected ferrous mineral compounds, has taken place late in the history of volcanic lavas, after some compounds have crystallized within the still fluid lavas. Other chemical reactions may take place between volatile compounds, or elements, within lavas, which may escape upon eruption without leaving any record of their reactions.

It is especially the gases acquired from wall rocks that are most likely to be capable of forming new compounds within rising magmas, since those inherent in magmas at great depths are more likely to have entered into whatever chemical combinations they were capable of forming with other magmatic constituents. Moreover, gases from near the earth's surface and from sedimentary strata are more likely to be oxidizing agents. Commenting upon the heating effects of possible combinations of hydrogen and carbon dioxide, of oxygen and carbon monoxide, and of the oxidation of ferrous oxide to ferric oxide, Day and Shepherd[6] remark that these and similar reactions may be the source of enormous volcanic energy, which reaches its maximum temperature at the surface itself.

[6] Day, A. L., and Shepherd, E. S. Bull. Geol. Soc. Am., 24, 1913, 600.

Another function of dissolved gases, diffusing from deeper parts of magmas and from wall rocks, is to increase the liquidity of lavas and to reduce their density, thereby promoting convection currents in more liquid portions of magmas, and in this manner tending to equalize temperature, and to maintain that of the top of lava columns.

By expanding, gases increase the volume of lava in a conduit, but this action takes place, probably, very near the earth's surface, causing the lava to rise in a crater or flow over its rim. By accumulating in the upper portion of a conduit, whose top is closed by solid lava, gases may attain such a vapor tension as to produce explosions, more or less violent. Similar action in a column of very viscous lava, or in one whose upper surface is very viscous, produces milder periodic explosions like those in a boiling spring or a geyser.

We may conclude, then, that the chief cause of the eruption of magma is the dislocation and fracture of the lithosphere, and that to some extent it may be aided by the slight expansion of magmas upon diminution of pressure, whether they are in the beginning wholly amorphous matter or in part crystals. It is aided when near the surface by expanding gases. Eruption may also result in part from hydrostatic pressure, due to the settling in some instances of overlying rock masses, which may rest upon bodies of magma within the lithosphere in a manner to be discussed later on. The crystallization of minerals in lavas within volcanic conduits must result in a shrinkage of the volume of the lavas, which may cause them to settle within their conduits to a slight extent.

The Process of Eruption

From what has been said concerning the possible cause of magmatic eruption, it may be imagined that the process would originate with some profound displacement of the lithosphere whereby the pseudo-rigid lower zone would begin to move upward. The volume of material set in motion might be very great, but the amount of movement might be slight, so far as distance of displacement is concerned.

If the flexure of the lithosphere were sufficient to rupture the overlying stiffer material, the more mobile matter, having nearly the same density as the material just above it, should move between the receding parts. No cavity should form in advance of the intruding matter, but there should be a differential flow of highly viscous substances, the less viscous advancing possibly in a wedge-like manner between the more viscous, or stiffer, flexible walls. The motion along the plane of shearing, or of differential flow, by reason of the internal friction, should lower the viscosity of the magma in this place. Owing to the approximate equality of mass and pressure between what may be called the wall matter and the penetrating moving magma, fissures filled with magma may exist at any depth, whereas the depth at which fissures filled with water may exist in rocks has a limit which depends on the crushing strength of rocks and on the mass or weight of the column of water.

The progress of magma upwards depends upon the dislocation of the fractured lithosphere. Molten magma is probably a passive agent at profound depths. It can not be the potential cause of eruption. Unless there has been a profound movement of the lithosphere, it seems

to be safe to say that magma will not rise, will not force its way upward; and in those places where fractured parts of the lithosphere are thrust tightly together magma will be prevented from rising.

To imagine magma moving upward of its own initiative, either by reason of violent expansive force, or of excessive heat, with which it may melt its way quietly through overlying rocks, is to assume an enormous accession of internal energy, either by reason of acquired gases, or of increased heat, the local generation of which must be accounted for.

The behavior of molten magmas in open craters as at Kilauea and Stromboli, or in volcanoes where periodic activity indicates a nearly free access of lava to the atmosphere, shows that the forces of ascension are almost in equilibrium with surrounding pressures, and that, except for the explosive energy of accumulated gases, and in some instances the sudden admission of bodies of water to molten lava as at Krakatau, in 1883, the behavior of magma in an open conduit is quiet, or even sluggish.

The progress of magma up through the rocks of the lithosphere is chiefly the progress of fractures induced in the frangible complex by warping and flexure. Near the surface of the lithosphere the explosive energy of pent-up gases asserts itself, and may become the immediate cause of surface eruption, determining the location and character of the outbreak. To picture the process of eruption and intrusion at some depth it is necessary to imagine the rupture of the lithosphere in general and also in detail, for it is the detailed character of some forms of intrusion within the upper portion of the rocky outer zone of the earth that has been the subject of lively controversy among geologists and petrologists.

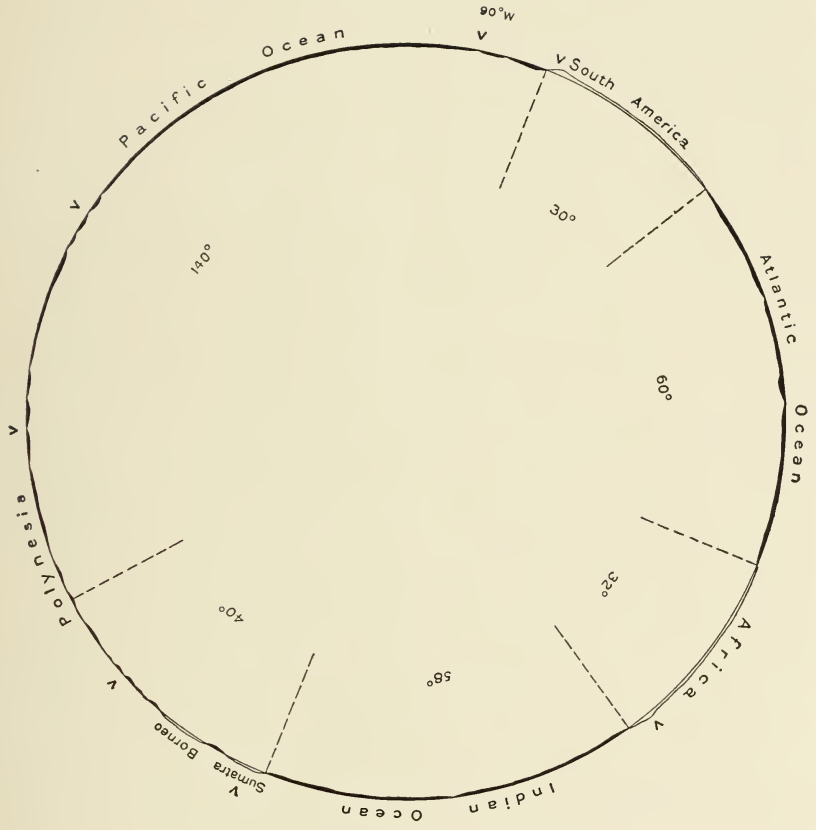

Fig. 51. Equatorial section of the Earth

Some idea of the possible process by which magma passes from its basal position upwards may be gotten from the consideration of a diagram representing in the crudest and most elemental manner the relative positions and possible movements of certain large segments of the earth in an equatorial section through its center (Fig. 51). In the diagram the segments correspond to the Pacific Ocean with an arc of about 140°, South America with about 40°, the Atlantic Ocean with 60°, and Polynesia with 40°. The differences in surface relief, if drawn to a natural scale, would not be perceptible, so they have been somewhat exaggerated in the diagram. The lithosphere is approximately parallel to the circumference of the circle, whatever may be the magnified impression of its uneven surface derived from our human point of view.

The slightly greater density of the segment beneath the Pacific Ocean has been considered to be the cause of its depression with respect to the adjacent continent of South America and the western island groups of Polynesia; and similar relations obtain with respect to the Indian and Atlantic Oceans and the intervening continents. The shrinking of the inner portions of these earth segments occasions a thrusting together of the stiff or rigid arcs of the circumference, or lithosphere, above each segment, assuming for initial simplicity that each segment acts as a unit. The preponderating influence of the Pacific segment is indicated by its great arc, which is more than one-third of the whole circumference, and three times as large as that of South America, or of Polynesia. In such a system of thrusting arcs, where should the major flexures and fractures occur, and where may volcanic eruptions take place? The simplest answer to this question would be: Where

the lithosphere offers least resistance to transverse components of the thrust stresses. The case may be illustrated in various ways.

If the lithosphere be represented by a horizontal plate, supported by a mobile medium and compressed from opposite sides in a line parallel to the plane of the plate, there should be no greater tendency for the plate to bend in one place than in another, if the plate were homogeneous in all respects. If, however, the plate were weighted at any place, it is evident that when flexure sets in after pressure exceeds the limit of rigidity of the material, the weighted part should bend downward; and if the weight were not in the center of the plate, but to one side, there would be a tendency for the unweighted half of the plate to bend upward. Similarly, if the plate were not homogeneous, but denser in some places than in others, the heavier parts would tend to bend downward, and the lighter upward. If the plate were not uniformly rigid, or were traversed by cracks, transverse shearing should take place, resulting in flexure and dislocation, with overthrusting. If the thrusts do not act in the direction of the plane of the plate, but at an angle with it, there will be a component transverse to the plate which will determine the direction of flexure. It is to be noted that the factors mentioned, unequal weighting, difference in rigidity, and fractures, do not produce the flexures, which are due to the thrusting stress; they only determine their location and direction.

Applying these principles to the case of the tangentially compressed lithosphere, it is evident that the direction as well as the location of the major flexures in the rock zone about the earth will depend on differences of weighting, or mass, or of support, and on differences

in the constitution and coherence of this zone. Thus it may happen that sedimentation may determine the place where flexure may set in, and cause it to be downward, though it may not be the actual cause; that is, it may not supply the requisite amount of energy to overcome the rigidity of the rock zone. In like manner, a slight shrinkage of substance beneath the lithosphere at any place may locate a downward flexure. Certainly the heterogeneous constitution of the upper portion of the lithosphere occasions the manifold complexities of flexures, foldings, and overthrust faulting observed in regions of pronounced thrusting, as in the Swiss Alps, and, to a less extent, in the Appalachian Mountains.

In order to understand how magmatic eruption may be connected with the major flexures of the lithosphere, certain cases of thrusting and fracturing may be considered as illustrating what may have happened in the regions bordering the great earth segments already referred to. The regions of active or recent volcanism are noted on the diagram by the letter V (Fig. 51). To explain the occurrence of lines of volcanic action along the west coast of South America in the Andes, which is the same in the Western Cordilleras of North America, one may imagine contiguous parts of the lithosphere thrust together, one with the major thrust advancing eastward from the Pacific segment, the other from the continent pushing westward. In the diagram (Fig. 52), the western part of the lithosphere is slightly depressed with respect to the eastern. The lower shaded portion is the hypothetical transition zone that grades upward into the more frangible portion. Tensile stress in the synclinal flexure permits the initial upward movement of magma. On the concave side of the flexure the rocks of the lithosphere are folded and fractured by reason

of the greater compression. The thrust from the west passes through the upper, rigid part of the lithosphere, and tends to shear the continental block with respect to the less rigid lower portion, so that there may be a tendency to fracture more or less horizontally toward the east. However, the fracture should rise into the continental mass according to its consistency, as there is a vertical component of the thrust that comes up from the Pacific segment, which tends to lift and shove the upper part of the continental segment of the lithosphere back toward the east, and results in folding and overthrusting in an eastward direction. The continental block may be split, as it were, or more probably may be fractured irregularly in the general direction indicated. It is to be noted that any fracturing originating at great depth is likely to pass upward into more and more numerous fissures as the more brittle upper portion of the lithosphere is traversed (Fig. 53).

As the upward component of the major thrust tends to lift the upper part of the sheared continental block, it permits the mobile lower portion to insinuate itself along the incipient fracture; or, perhaps, it may be better to imagine that along the plane of shearing a slight reduction in the pseudo-rigidity of the material takes place, permitting its movement along this plane, and in this manner it may be possible for a separation of the fractured parts of the lithosphere to take place, molten magma advancing as far as the equilibrium of the system, *thrust — gravitation — rigidity of rock — viscosity of magma,* may permit. In such an adjustment of forces and blocks of lithosphere the flow of magma would not be up vertical pipes or conduits, as so commonly represented in diagrammatic sections of volcanic regions, but

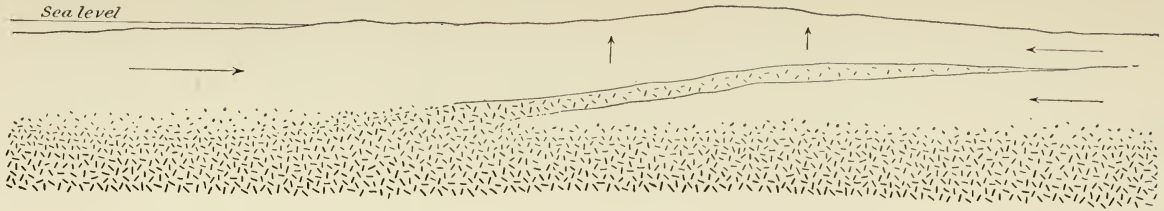

FIG. 52

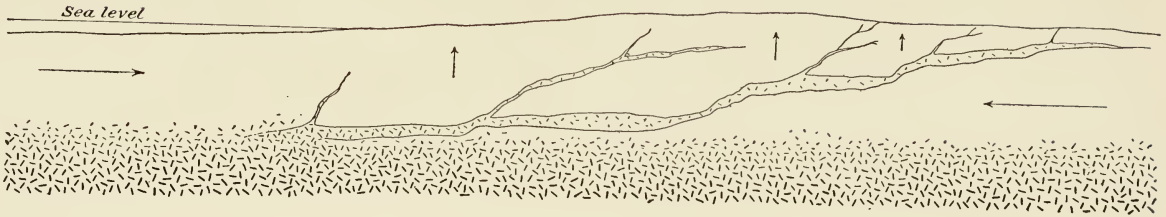

FIG. 53

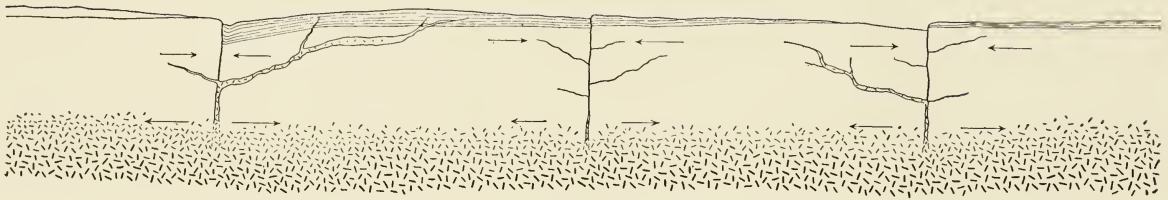

FIG. 54

HYPOTHETICAL SECTION OF THE LITHOSPHERE, SHOWING THREE FORMS OF FRACTURE AND MAGMATIC INTRUSION

would be along inclined fissures from the bottom of the lithosphere.

If the inclination of the Pacific thrust had changed during a long period of time, from Mesozoic to Recent; if it had been more nearly tangential in the beginning of this period than at present, owing to the gradual depression or flattening of the oceanic arc, the sea deepening off the coast during this period and the direction of thrust becoming more inclined to the earth's circumference, then the upward component of the Pacific thrust should have been greater in more recent times, and the resultant fracturing should have been more effective nearer the west coast than farther east, or should continue in the west after it had ceased in the east. Or the resulting change in action might be thought of as the bending of a plate of heavy, brittle material which began with a broad, gentle arching accompanied by fractures that were scattered throughout the broad arch, and continued with a stronger and stronger bending of the western end of the plate. This would correspond in a general way to the dynamical history of the Western Cordilleras of North America from the Rocky Mountains to the Pacific Coast. Fracturing and dislocation with eruption of molten magmas took place in various parts of this region in late Mesozoic times and throughout the Tertiary period, but in late Tertiary and early Modern times volcanic activity continued near the coast, along which seismic disturbances with appreciable dislocations are still taking place.

The shifting of volcanic vents and of lines of volcanic activity with the progressive shifting of faulting and folding has been likened by Suess to the opening and closing of crevasses across a glacier which is being bent as the ice creeps over an obstructing ledge. In the

suggestion here presented, the rupturing body is not moving over an obstacle, but is undergoing a set of stresses that are shifting their direction because of the warping of the body from tangential thrusting and gravitational depression.

The volume of magma erupted, the distance traversed by it laterally, and the elevation, or horizon, in the lithosphere to which it rises, must depend upon the relative values of the factors in the equilibrium already mentioned. The greater the resistance of the uppermost portion of the lithosphere, the greater should be the region affected, and the profounder the depth to which the lithosphere should be disturbed, and probably the greater the volume of magma displaced or erupted.

The Cordilleras of North and South America along the western margin of the continental segments with their abundant eruptions of volcanic lavas accord with this conception. The great intrusions of magma in Peru and Bolivia, according to Steinmann,[7] penetrated fractured and faulted strata, and the igneous eruptions in general are subsequent to the principal faulting of the Cordilleras. The ranges of volcanic islands and the ocean troughs along the western margin of the Pacific segment off the coast of Asia show a similar relation. Between the great Pacific and Indian segments the Polynesian archipelago is the seat of vigorous active volcanism, and along the margins of the Indian and African segments there has been, and still is, considerable volcanic activity. But there is no modern volcanism between the evenly balanced segments of South America and the South Atlantic.

In parts of the lithosphere where there is a depression

[7] Steinmann, G. *Geol. Rundschau*, 1, 1910, 29.

or synclinal flexure there is tensile stress in the lower portion of the stretched plate-like mass, and if the arc of the curve is sufficiently flat there may be tensile stress throughout its entire thickness, but it should be greatest on the lower, or convex, side of the arch, in which part fracture should commence when the limit of cohesion is passed.

In a broad synclinal plate of somewhat heterogeneous material, fractures should originate at various places and extend in nearly parallel lines across the direction of tensile stress, but if the plate were not completely ruptured the fractures may not extend entirely through it, or for equal distances in the direction of cracking. In like manner the warped lithosphere may fracture in a set of nearly parallel fissures that began to form in various places and may have proceeded to different distances laterally and vertically, which is well illustrated by the system of faults in the high plateaux of Utah, already referred to (Fig. 40). The resultant, partly severed blocks, may sink where heaviest, or where most nearly severed from adjacent ones, still further increasing the irregularities of the warped plane. Individual blocks may bend lengthwise or be tilted against their neighbors, thrusting their edges against one another with greater or less violence according to their masses and the nature of their displacement.

The deepest fractures starting from the zone of potential magma should permit its eruption and intrusion between blocks that tend to part from one another by reason of the tensile stress. Other blocks upon being dislocated may be forced together and prevent the rise of magma. This mode of eruption may be illustrated crudely by the accompanying diagram (Fig. 54). In the case of block-faulting, it may rarely happen that volcanic

lavas reach the earth's surface through the fractures along which their eruption originated. Such fractures, if open at the bottom, are most probably closed at the top near the earth's surface, owing to the tilting and crowding together of the upper ends of large blocks. This local thrusting probably occasions transverse fracturing of the upper parts of faulted blocks, and the intrusion and eruption of magma through these subsidiary fissures, in a manner to be discussed later on in connection with particular modes, or forms, of intrusions. This method of fracture and eruption may explain the abundance of small intrusions of apatite-mica-peridotite in the coal fields of Darjiling and elsewhere in Northern India which appear to be the upper portions of sunken faulted blocks, according to Sir Thomas Holland.

Block-faulting under tensile stress appears to have fractured the lithosphere beneath the Great Basin of Utah and Nevada, and in the region of the Great Rift Valley in East Africa. In each of these regions parallel fractures accompanied by the unequal subsidence of faulted blocks of lithosphere are characteristic structural features, with which are associated contemporaneous eruptions of volcanic lavas. But in the Great Rift Valley the trough-like structure is much more pronounced and localized, that is, laterally, for though comparatively narrow, it is exceedingly long.

The great deeps of the ocean are in some instances trough-like depressions; in others, great basins, or synclinal flexures, which no doubt have been accompanied by deep-seated fractures, some of which may have traversed the depressed regions and have permitted the eruption of volcanic lavas, as in the chain of the Hawaiian Islands. In other instances, lavas may have reached the surface to one side of the synclinal troughs,

and it may be a question whether their conduits belong to the class of strictly tensional openings, or to those originated beneath thrusts. In fact, the blending of the two kinds of processes by reason of the complex structure of the fractured lithosphere has been clearly indicated in the discussion. While it is possible to conceive of distinct processes of eruption, the warping lithosphere combines thrusts and tensions in such an intricate fashion that the distinction suggested has only an academic value, which is apt to be the case with most attempts to discriminate, or establish, simple types of processes, or of products, in the blended complexes found in Nature.

The conception of magmatic eruption which has been suggested involves a comparatively rigid upper zone of lithosphere, grading downward into a pseudo-rigid zone having essentially the same chemical composition as the upper one. It also involves the idea of a warping lithosphere adjusting itself to a contracting central mass; the warping producing fractures along which the highly viscous matter moves according to differences of stress, and in the process becomes less viscous as it approaches higher levels, attaining its maximum liquidity where the gaseous constituents have their freest movement, or are concentrated in greatest amount; magma coming to rest in equilibrium with surrounding wall rocks at various depths, and in some places finding itself in equilibrium with the atmosphere at the surface of the earth.

CHAPTER VII

INTRUSION OF IGNEOUS MAGMAS WITHIN THE LITHOSPHERE

The magmas of intrusive rocks, that have been exposed to view at the earth's surface, have in most instances intersected sedimentary strata and the metamorphic rocks associated with them, and must have reached upper portions of the lithosphere before they solidified. In many instances it is evident that the wall rocks produced a chilling effect on them, showing that they were in the zone of moderate temperatures within a few miles of the surface of the earth. Intrusive bodies range in size from those that are very small, to those measurable in cubic miles, and it is the process by which they acquired their various shapes and dimensions, and came to be intruded within the rocks surrounding them, that is one of the chief elements in the problem of volcanism.

Between the upper part of the lithosphere, in which the bodies of solidified magma occur that have come within the reach of our observation, and its base, below which may be located the primary source of molten magmas, there must be a very considerable interval embracing the middle and lower portions of the lithosphere which are below the range of our observation, into which magmas have been intruded and through which they must pass to reach the uppermost zone and the earth's surface. What may have happened to the magmas that never rose above the deeper-seated zones

must remain a matter for speculation only, but the experiences of those magmas that reached higher levels, and formed the intrusive rocks with which we are familiar, may be inferred in part from certain of their characteristics, especially their variability in composition. This variability, because of the small volume of some bodies of different rocks, and because of the intimate and frequent association of extreme varieties, and also because of the constant recurrence of series of variations, indicates the action of localized processes whereby the different varieties may be formed from magmas having a more nearly average composition for particular series in each district or region. In short, the variableness in the composition of the igneous rocks in one district indicates that their magmas were derived by some process of separation, or differentiation, from larger volumes of magma that had an intermediate composition, or one that was an average for the district.

After the eruption of lavas in a variable series, having more and more diverse compositions from intermediate to extremes, there may be erupted in the same region a subsequent series of lavas, the earliest of which have intermediate compositions, from which it may be inferred that the earliest eruptions in each series came from a source or reservoir of magma that had not been differentiated; while the later eruptions of lavas, having more variable compositions and in some instances smaller volumes and more restricted occurrence, were derived from reservoirs of magma that had undergone differentiation and were smaller in size.[1]

For example, the earliest magmas in the great series of Tertiary eruptions in the region of the Yellowstone

[1] Iddings, J. P. Quar. Jour. Geol. Soc., 52, 1896, 606.

National Park may have come from the primary reservoir or zone of pseudo-rigid magma, and may have been the immediate outflow through the earliest fissures in this region at this time; while the magmas of later eruptions in the series may have remained for long periods within deep parts of the lithosphere, and gradually reached higher levels as the process of eruption lifted successive masses of lava to the surface of the earth.

Since the volumes of lava erupted from volcanic vents in particular instances are very small, they must have come from short distances within the volcanic conduits, indicating a gradual though spasmodic movement through such channels; and as the intervals between some flows are decades and centuries, molten magmas must exist in a fluid condition for extremely long periods within the channels through which they reach higher levels in very many instances. It is in this slow ascent through lower and middle zones of the lithosphere that variations in the composition of magmas are supposed to take place, and since the volume of differentiated bodies of lava may be very great, as in the case of the rhyolites of the Yellowstone Plateaux and the basalts of the Snake River, the size or capacity of some of these channels must be considerable, measurable in cubic miles. Such bodies of differentiated and differentiating molten magma are reservoirs that may be called subsidiary reservoirs or magma basins, to distinguish them from the greater volumes of undifferentiated magma, whose composition may be nearly permanent, because of the almost constant temperature at which they exist for enormous lengths of time.

The shapes and positions of the channels or subsidiary reservoirs, through which molten magmas pass within

the lower and middle parts of the lithosphere, should vary according to the dynamical conditions that produced fractures and the physical status of the wall rocks. In the lowest portion the conditions should be nearly the same as those imagined for initial eruptions within the zone of pseudo-rigid magma. In the middle portions of the lithosphere, they should be more nearly like the conditions attending fracture and intrusion of magma in the upper zone of brittle rocks.

In the lowest region, the channels may be larger than higher up, and their boundaries may be ill-defined because of the similarity in composition and physical condition of the moving magma and the less mobile wall matter. The movement at the greatest depth may be a differential flow, the middle of the stream having an appreciable velocity, which decreases to zero at the sides. Higher up, contrasts in temperature and in viscosity between moving magma and wall matter should be greater, and the boundary between the two should be more distinct, but the composition may be nearly the same in both. Indeed, the chemical composition of primary magmas may be nearly the same as that of the lower portion of the lithosphere through which they begin to rise, though each may be somewhat heterogeneous in composition within moderate limits; and it may be only in the more or less highly differentiated outer zone that magmas may flow through rocks differing considerably from them in composition. Loss of heat is probably the chief factor in bringing about the differentiation of molten magmas, and the more heterogeneous, upper portion of the lithosphere is probably that in which temperatures are notably different from those of molten magma.

We may imagine, then, that within the middle of the

lithosphere, in regions where profound flexure has induced fractures and dislocation, molten magmas have risen from lower zones and in some instances have formed great bodies of viscous magma, from which they may rise into still higher positions whenever overlying rocks are so fractured as to permit their eruption.

It is possible that fracturing may take place in such a manner that magma may flow almost without intermission into the outermost zone of rocks, or out upon the earth's surface. In such a case, the composition of the lava may be that of the original magma with little or no modification during its passage upward. In other cases, fracturing may continue to take place at intervals for long periods of time as one portion after another of the overlying rock mass yields to accumulating stresses, so that new fractures may open new channels of eruption through which magma from older channels and from the subsidiary reservoirs may rise into the uppermost rocks. These later fractures may traverse solidified bodies of magma previously erupted, and in rare instances may reopen fissures recently filled with magma that had not completely solidified, as in certain instances in the Isle of Skye, described by Harker.[2]

As to the length of time required for the passage of molten magma from great depths to the earth's surface, we have no means of forming an estimate. The amount of displacement of blocks of lithosphere is very large in some cases, and if the movement had been accomplished in a short time the effects at the surface must have been catastrophic. Displacements along fault planes amounting to 15,000 feet and more are known to have taken place, but it is generally believed that they progressed

[2] Harker, A., and Clough, C. T. Geol. Survey, Great Britain, Memoir, *Tertiary Igneous Rocks of Skye,* 1904.

as a series of small dislocations, following one another at remote intervals through a very long period of time, perhaps thousands of years. It is possible that large bodies of magma have been formed by very slow movement of very viscous magma, creeping at an almost imperceptible rate in some instances, but moving more rapidly at times when a sudden rupture and displacement of the surrounding rocks took place; a movement that may correspond to only a few feet of linear displacement, but may have been accompanied by a violent jar and earthquake.

As to the directions along which fractures may take place, which determine the positions of channels and the shapes of conduits and reservoirs of magma, it is to be remembered that the causes of fracture are chiefly shearing due to thrusts, and rupture due to tension, and that these operations may be combined in endless variety and detail as the more or less rigid and elastic material bends in some places until it ruptures across the stretched parts, then is thrust against some other part until its limit of resistance is exceeded, when it cracks along a shearing plane, and so on through a succession of thrusts and flexures, rapidly or very gradually as the case may be; not in a single series of successive fractures traversing a warping mass, but in multiple series of contemporaneous cracks that ramify through the body in a more or less intersecting system. These fractures may divide it into blocks whose shapes and dimensions depend upon the directions and intensities of the initial stresses, on the consistency, cohesive strength, elasticity, and brittleness of the rock material, as well as on its homogeneity or internal structure. In some instances, the fractured rock may split into thin plates owing to a laminated structure, as in some crystalline schists and

in shales and fissile limestones. In other instances, the rock may shatter into angular fragments or blocks, as in massive crystalline rocks and quartzites.

In general, it may be expected that profound flexures in the lithosphere will be about axes that are nearly horizontal, or parallel to the earth's surface, so that ruptures across them will be nearly vertical, or steeply inclined to a horizontal plane; although fractures nearly parallel to the earth's surface might be occasioned by highly inclined folds. On the other hand, thrusts due to the crowding together of parts of the outer zone of the lithosphere act more nearly in planes parallel to the earth's surface, and the resultant fractures from shearing should be nearly horizontal. However, minor thrusts may result from the crowding together of smaller blocks at various angles, and the shearing so produced may take place at corresponding inclinations, so there can not be a rigid relationship between the position of fracture in the lithosphere and the nature of the stress producing it. Nevertheless, it is probably true that most horizontal major fractures have resulted from great thrusts, and most nearly vertical ones have been produced by great flexures, as Gilbert and others have pointed out.

However, the fracture of a homogeneous body, unsupported on the sides, follows a plane inclined to the direction of thrust and the free sides of the body, as in the case of a cubical block crushed under two-sided compression; consequently, the fracture produced by the thrusting of two blocks of the lithosphere should rise upward toward the free side of the fractured block, that is, toward the earth's surface. It is to be remembered that the lithosphere has about the rigidity of plate glass, and that below the stratified rocks it should behave

toward great stresses as though it were almost homogeneous, for it is known that joints and fractures intersect massive crystalline rocks in planes that traverse various crystals and various kinds of veins and dikes without notable deviation.

We may imagine, then, fractures traversing the lithosphere for very long distances, many miles in some instances. Fissures and fault planes have been traced with some interruption for hundreds of miles; some faults in the Appalachian region have been traced for three hundred miles.[3] The Great Pfahl quartz vein in Austria and Bohemia extends for about ninety miles,[4] and the system of meridional faults through the Great Rift Valley extends for over 3,000 miles, according to Suess.[5] Nearly horizontal fractures in sedimentary formations into which igneous magmas have been intruded are known to be continuous for many miles; a classic example is the great Whin Sill of basaltic rock in Carboniferous strata in Northumberland, England, which has been followed for nearly eighty miles. Its maximum thickness is only about seventy feet, and it shifts its position from lower to higher strata through a known height of 1,560 feet.[6]

Great thrusts like those which may be imagined to take place between major segments of the lithosphere, that between the Pacific Ocean segment and those of North and South America, for example, may fracture the lower and middle portions of the lithosphere for great distances, permitting magmas to intrude themselves far eastward and upward toward the surface.

[3] Keith, A. U. S. Geol. Survey, Atlas Folio, 147, 1907.
[4] Suess, E. *The Face of the Earth,* vol. 1, 1904, 208.
[5] *Ibid.,* vol. IV, 1909, 268.
[6] Geikie, A. *The Ancient Volcanoes of Great Britain,* vol. II, 1897, 2.

These magmas, having nearly the same density as the wall matter and a hydrostatic pressure corresponding to their depths below the earth's surface, are able to support whatever load is above them, and for these reasons may permit the walls of the fracture to separate vertically or laterally, whenever the stresses acting within them tend to move them apart.

This may be illustrated diagrammatically by Figure 52, already alluded to, which represents a hypothetical section along an intrusion that is supposed to have started with a deep synclinal flexure of the lithosphere west of the continental mass, beneath the margin of the Pacific Ocean. The shear fracture is supposed to pass nearly parallel to the surface, rising eastward. The length of the section in an east and west direction is about two hundred miles, and the thickness of the lithosphere is assumed to be about thirty miles, in conformity with earthquake phenomena, according to Sir John Milne. The shaded zone at the base of the section is intended to represent the transition of the lithosphere into the zone of pseudo-rigid matter, the assumed source of molten magmas. The diagram may be considered the simplest expression of the possibility of thrust fracturing. More complex fracturing is more probable, and is illustrated by Figure 53.

The lack of homogeneity in the mass of the lithosphere permits the unequal warping or flexure of the parts separated by fracture, that is, beneath, as well as above, the planes of fracture; so that with the intrusion of dense, viscous magma it is possible for the upper and lower walls to separate sufficiently to allow large volumes of magma to insert themselves in some places, which become subsidiary reservoirs, in which magmas may

remain fluid for great lengths of time, according to the volume of magma and the temperature of the wall rocks.

In the case of block-faulting such as has been imagined to take place in regions of subsidence with the production of trough-like depressions, like the Great Rift Valley, or with the formation of monoclinal faulted ranges like those in the Great Basin of Utah and Nevada, the initial fracture at the base of the lithosphere, due to tension, may be nearly vertical, as in Figure 54. Into such a fracture magma may intrude itself for considerable distances between the separating walls, but, as previously remarked, it may seldom happen that magma is able to traverse the fracture all the way through the lithosphere and flow out upon the surface of the earth. The faulted blocks are likely to settle together because of their great weight, thrusting against one another in their upper portions, which may become fractured laterally in the manner already described. Subsidiary reservoirs of magma may exist within the major vertical fracture as well as in higher lateral ones.

Subsidiary reservoirs of magma may be variously shaped, occupy diverse positions, and be of very different sizes. They are undoubtedly extensive in the plane of fracture, but much less so in a direction at right angles to it. They may occupy areas ranging from a few square miles to hundreds of square miles in some regions, but may seldom be as thick as five miles. They may be nearly horizontal, or may be inclined at any angle, from horizontal to vertical. Their boundary walls may be nearly parallel in some instances, but not necessarily straight planes; more probably, warped planes, or uneven ones with angular step-like interruptions, according to the direction of the planes of fracture, the consistency of the rock zone, and the amount of shear

or of faulting accompanying the displacement and the intrusion of magma.

Shapes of Intrusive Bodies

While the character of intrusions within deeper parts of the lithosphere must remain a matter of speculation, liable to various representations according to hypotheses regarding the interior of the earth, the character of intruded bodies of magma within the outer zone of rocks, which have been exposed to view by denudation and faulting, should be capable of actual determination, both as regards their form and position with respect to surrounding rocks, and ultimately as to their manner of intrusion. That this has not yet been accomplished in many instances is due to the fact that the relation of large bodies of intrusive rocks to surrounding ones is not so evident in most instances as descriptions of them often lead one to infer. Too often, the greater part of the rocks are concealed by débris and vegetation, very little is visible of the actual contact between the intruded mass and its containing walls, and that which is exposed is often inadequate to determine the shape and position of the intruded mass, so that the form of the greater part of the body is imagined, and this fact is not clearly stated in the description of it.

Owing to great diversity in the imaginations of individual petrologists and geologists, and to the necessarily subjective character of the imagination, there is wide divergence in the interpretation placed upon the meager evidence available in partial exposures of many intrusive bodies; and there is also in some cases a great difference of opinion as to what constitutes adequate observation of exposures that are available. For these reasons it

happens that there are pronounced differences of opinion regarding the shapes and sizes of certain large bodies of igneous rocks, and very different hypotheses as to their manner or process of intrusion. These differences bear a direct ratio to the size and consequent indefiniteness of the intruded mass, that is, they are greatest with respect to those large, ill-defined bodies of granite and other coarse-grained rocks known as batholiths; less divergent, though distinct, regarding smaller dome-shaped bodies called laccoliths; and slight when thin intrusive sheets, or sills, and dikes are under discussion.

The original definition of a batholith proposed by Suess was probably more nearly correct, except for one feature in its supposed mode of formation, than subsequent definitions that have attempted to explain the intrusion of great bodies of magma, the lower sides of which have not been exposed to view by denudation or faulting. Suess at first imagined that in the dislocation of the lithosphere, portions of it were bent apart, leaving great cavernous spaces into which molten magma was subsequently intruded.[7] The defect in this suggestion lies in the assumption that large, empty spaces could form within the lithosphere, and that rock at considerable depths would be strong enough to support its own weight. Had he suggested that as the lithosphere in places tended to part, molten magma might enter the fracture, and because of its density and hydrostatic pressure might permit the fractured parts to separate, the magma supporting its share of the overlying load, his explanation of the formation of a batholith would have been reasonable, and the most probable of any that have been suggested. It is this modification of Suess's

[7] Suess, E. *The Face of the Earth,* vol. I, 1904, 168.

suggestion that appears to the writer to be the most rational one, and to be entirely adequate so far as our present knowledge of the lithosphere and of magmas permits us to reason on the matter.

Batholiths are great bodies of igneous rocks without characteristic shapes, usually irregularly outlined, whose chief distinction rests upon the fact that the lower limit, or base, is not exposed to view and the upper surface has been uncovered by erosion, so that the roof is a matter of speculation and the bottom is wholly unknown. It is not to be assumed that, because a body of coarse-grained igneous rock, exposed by erosion at the surface of the earth, has no present covering of other rocks, it never possessed one. The probabilities are almost wholly in favor of its having had one, and in some instances portions of a roof are visible. In like manner it does not follow that, because the bottom of such a large body is not exposed to view, it does not exist, or is more than a few thousands of feet below the part exposed, which itself is seldom more than 2,000 or 3,000 feet in vertical extent. In exceptional instances, as in the great escarpments in the Yosemite Valley, there are exposures of continuous massive rock which are 4,000 feet in height. The etymological significance of the term, batholith, is merely a deep body of rock, and Suess, who first employed it, described such a body as a "wahre Kuchen," a term equally applicable to laccoliths, between which and batholiths there may be gradations.

It has become a custom in drawing diagrammatic sections through such bodies, to represent them as bottomless, as descending vertically toward the center of the earth. These diagrammatic vertical columns have been intended in some cases to indicate merely that the magma came up from unknown depths, and that their

Fig. 55. Granite Veins in gneiss, Quinsigamond quarry, Worcester, Mass.

A. Keith, U. S. Geol. Surv.

position and size in the diagram were not to be taken seriously. In other cases they have been intended to convey the impression that the magma rose vertically upward through the lithosphere; according to some hypotheses, by dissolving the rocks in its path;[8] according to others, by a process of splitting off overlying slabs of rock and letting them sink through the rising magma to indefinite depths, there to be melted up into new magma. This latter process has been called "overhead stoping."[9]

Objections to the hypothesis that magmas dissolve their way through the lithosphere rest upon the chemical evidence that intruded magmas have not dissolved and blended with the wall rocks to any considerable extent in parts of the lithosphere where they at present exist and can be studied. Granites have similar compositions whether they are intruded in limestones, sandstones, shales, granites, or other kinds of igneous rocks.

It is well known that granitic material permeates schistose rocks in such a manner, in some instances, as to indicate that granitic magma penetrated between layers of these rocks and formed a laminated crystallized complex like some gneisses. In places, sheets of massive granite appear as intrusions between such complex layers, as is clearly shown in the photograph of a quarry at Quinsigamond, near Worcester, Massachusetts (Fig. 55). In some instances, the intruding granitic magma may spread apart the fissile layers of schistose rock, may soften them, and to some extent dissolve the smaller fragments, and by moving may distort the complex irregularly. This took place in

[8] Michel-Lévy, A. M. Bull. Serv. Carte géol. France, 36, 1893, 36. Barrois, Ch., *Ann. Soc. géol. Nord*, 22, 1894, 181.

[9] Daly, R. A. Am. Jour. Sci., 15, 1903, 269.

marginal portions of the Whiteside granite near Morganton, North Carolina, described by Keith and shown in Figure 56. In cases of this kind, as Sederholm has remarked in describing similar intrusions in Finland, the wall rock has been fractured, in some instances for a thousand feet from the contact with the main body of magma.[10] The fractures have been filled with aplite and pegmatite; the outlines of the inclosed fragments, often sharp and distinct at a distance from the main mass of magma, in some cases become obliterated by blending with the magma. But, he adds, "in general the cementing granite does not appear to have been very considerably influenced by the basic rock which it dissolved," from which we may conclude that it did not dissolve much of it. Objections to the hypothesis of intrusion by solution also rest on the fact that a great excess of heat must be stored in the rising magma, and that such excessive heat must be localized, for if generally distributed within the zone of primitive magma, all the lower portion of the lithosphere should be similarly consumed.

The same objections hold against the hypothesis of overhead stoping, which is a modification of the solutional hypothesis, introducing the mechanical breaking down of overlying rock through heating to a temperature at which the expansion of the surface of the wall rock is assumed to cause it to spall off, and by reason of greater density fall through the molten magma until it reaches a depth at which the magma is hot enough to dissolve it. This hypothesis obviates the necessity of a magma showing any chemical evidence of its solution of wall rock, but does not avoid the possibility of a

[10] Sederholm, J. J. Congrès géol. Intern., 12th Session, Toronto, 1913.

viscous magma being caught in the act, so to speak, of undermining the foundation of geology, the lithosphere. Up to the present time, no magma has been so convicted beyond reasonable doubt, and the natural inference is that none of them have been guilty of such an attempt.

It has been suggested that gaseous exhalations from intruded magma might corrode and dissolve mineral constituents of wall rocks, and carry them off through flowing solutions, forming spaces into which molten magma would move, and that intrusion on a vast scale might take place in this manner. Such a hypothesis postulates copious exhalation of gases, the permeability of wall rocks, the solubility of the mineral constituents, and the possible escape of aqueous or gaseous solutions through rocks remote from the contact zone. This conception seems to be based on the phenomena of gaseous activity in lavas at or near the surface of the earth, especially in a crater like that of Kilauea.

The gaseous activity of rock magmas within completely filled closed vessels, or reservoirs, with almost impermeable walls, under great pressures must be an altogether different matter. The amount of gas available for diffusion may be comparatively small, owing to the possible chemical combination of the elements under high pressures. The greater viscosity of magmas under pressure, and of gases at higher temperatures, the probable absence of capillary spaces in wall rocks at great depths, and the probable approximate equality of pressures within the magma and in surrounding rocks, render it highly probable that the amount of gases capable of passing outward from molten magma under such conditions is an almost negligible quantity. Near the earth's surface there may be conditions more favorable to the process suggested, and the phenomena of

contact metamorphism in some instances indicate the active diffusion of gases from intruded magma; but the questions arise, When were the gases given off? and to what extent were rock minerals removed and their places occupied by matter from the magma? How much of it was molecular replacement and recrystallization in situ? and to what extent did molten magma penetrate pores or cavities in unfractured wall rock?

The gas available must be liberated from combination, or solution, in the magma. Its rate of diffusion depends on the viscosity of the magma, as already said, and on differences in vapor pressure within the magma and within the surrounding rocks; it also depends on the porosity of the wall rocks and the viscosity of water within its pores or capillary spaces. The solubility of the mineral constituents of surrounding rocks depends upon their chemical composition and crystalline character, as well as on the character of the transfused gases or aqueous solutions. Moreover, the distance to which such solutions may travel through rocks remote from the molten magma must depend not only on the permeability of such rocks, and on differences of pressures, but on the question as to whether the solutions are dilute or saturated, for saturated solutions would deposit matter as they became cooler, and should close their own passages.

The gases that escape from intruded magmas are more likely to be more abundant as the magma begins to crystallize into silicate minerals free from water, sulphur, carbon, and nitrogen, for these elements concentrate in the liquid portion of the magma, not yet crystallized, and by increasing its liquidity and the vapor pressure also increase their ability to diffuse into pores or fissures within surrounding rocks. Upon gradual

FIG. 56. WHITESIDE GRANITE WITH INCLUSIONS, NEAR MORGANTON, N. C.

A. Keith, U. S. Geol. Surv.

lowering of temperature through cooling, the consequent contraction of the surrounding rocks may lead to fracture and fissures, into which not only the gases, but the more liquid residual magma, may penetrate, producing well-known aplitic and pegmatitic intrusive veins. Such veins, it will be remembered, traverse not only the rocks which surrounded the once molten magma, but also the marginal portions of the crystallized magma, or intrusive rock, which must have contracted and cracked at the time of the aplitic intrusion. It seems highly probable that the hypothesis of gaseous corrosion is inapplicable to the problem of magmatic intrusion on a large scale. It has to do with the processes of contact metamorphism, especially in their later stages.

Fracturing of the lithosphere by thrusting and flexure is sufficient to explain the major phenomena observed in connection with the large, irregularly shaped bodies of intruded rocks called batholiths, for it must be remembered that within the more brittle upper part of the outer zone, the fractures produced by warping intersect one another at various angles, and often in curved planes, and that when molten magma is advancing along a system of fractures from below it permits the separation of blocks of fractured rocks that could not otherwise separate because of their great weight. A viscous magma whose mass, or density, is ten-elevenths as great as that of the overlying rocks, whose crushing strength or rigidity in a closed space is as great as it has been shown to be by the experiments of F. D. Adams and E. G. Coker, is capable of supporting rock having a thickness or depth in the lithosphere of many thousands of feet. If the shearing strength were only 22,000 pounds per square inch, it could support about 193,000 feet of rock, or a thickness of about thirty-six miles. It

is possible, then, for an intrusion of viscous magma to support a roof of rock of very great extent.

The quartz-diorite batholith that forms the center of the Andes in Argentina, near latitude 41° South, according to Bailey Willis and C. W. Washburne, is exposed for a width of about thirty miles in an east and west direction near Lago Nahuel Huapi, and is topped by a nearly horizontal roof of crystalline rocks, beneath which it was intruded in Tertiary times. The contact between the roof and the underlying mass is plainly visible in numerous places and is seen to be clean-cut, without fragments of the roof displaced or partly suspended within the intruded mass, which is exposed for a depth of 3,000 feet in intersecting valleys (Fig. 57). In this great body of white, granite-like rock there are few intersecting bodies of other igneous rocks, which abound in the quartz-diorite intrusions in the Cordillera of southeastern Alaska described by F. E. Wright,[11] or in the great granodiorite intrusions in the Sierra Nevada in California, as described by Lindgren and Turner.[12] In these regions successive intrusions of smaller bodies of magma have cut earlier ones, and innumerable veins of pegmatite traverse the upper portions of the granodiorite and overlying wall rocks.

These great intrusions which have been described as batholiths, extending in a more or less connected chain of elongated exposures from Alaska to Patagonia, were most probably intruded through fractures produced by flexures and thrusts between the Pacific and continental segments of the lithosphere in the manner already suggested. The folded and sheared strata to the west

[11] Wright, F. E., and C. W. U. S. Geol. Survey, Bull. 347, 1908, 61.

[12] Lindgren, W. U. S. Geol. Survey, 17th Ann. Rep., part 2, 1; Turner, H. W., *ibid.*, part 1, 521.

FIG. 57. BATHOLITH NEAR LAGO NAHUEL HUAPI, ARGENTINA

Bailey Willis

of the Sierra Nevada in California and of the Coast Range in British Columbia, and the overthrusting toward the east indicate that the upper part of the lithosphere yielded to a thrust from the west beneath the Pacific Ocean. Other great batholiths of this kind occur on the Ranen Fjord, in Norway, the under side of several of them being partly exposed.[13] Similar batholithic intrusions may result from basin-like subsidence as already suggested in connection with block-faulting.

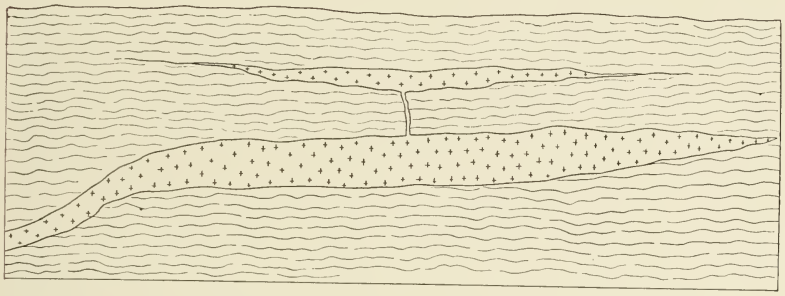

FIG. 58. HYPOTHETICAL SECTION OF ONE FORM OF POSSIBLE BATHOLITHIC INTRUSION

A synclinal depression above a subsidiary magma reservoir may result in an intrusion into overlying strata whereby a batholith may form directly above it, as indicated in the diagram (Fig. 58). The tension in the lower part of the depressed roof might fracture it so as to permit the rise of magma to a higher horizon, where it might meet a plane of weakness or of least resistance, in a fissile bed of shale, or other plane of parting, which would allow it to intrude itself laterally. Here it might spread to a considerable distance and support the uppermost rock as a roof, either lifting it or maintaining its

[13] Norges Geol. Unders. aarb., 1909, V; 1910, III; 1911, I; and No. 67, 1913.

former position, while the lower portion was depressed until equilibrium was established between mass, rigidity, viscosity, and whatever stresses obtained in the surrounding lithosphere. Whether such an intruded body should be called a batholith, laccolith, or sill is a matter of definition, which is partly a matter of opinion, partly one of convention, and depends upon whether the definitions are based on the shape, size, or manner of formation of intruded bodies, a subject on which petrologists are not agreed.

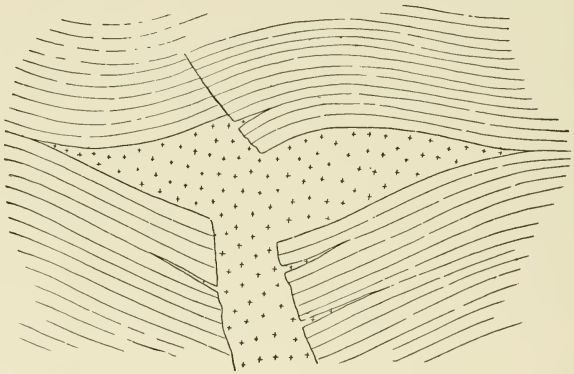

Fig. 59. Hypothetical section of ethmolith
W. Salomon

The great intrusive mass of granite and tonalite of Mount Adamello, in Lombardy, is surrounded on the southern half by strata dipping inward toward it, in places showing flexure and step-fracture, as though the intrusion had accompanied a basin-like subsidence. According to W. Salomon,[14] this intrusive body is intermediate in form between a laccolith and a stock, and having a funnel-like shape has been called an ethmolith,

[14] Salomon, W. Tschermaks Min. Petr. Mitth., 17, 1897, 109, and Sitz. d. Berliner Akad. Wiss., 1903, 307.

an ideal section of which is represented in Figure 59. Somewhat similar positions of surrounding strata characterize the monzonitic intrusions at Predazzo and Monzoni, in the Tyrol.

The stratified rocks surrounding the great Buschveldt granite in the Transvaal, according to G. A. F. Molengraaff, dip beneath the intrusive mass, in places exhibiting step-like faulting.[15] The structure suggested may be represented diagrammatically by Figure 60.

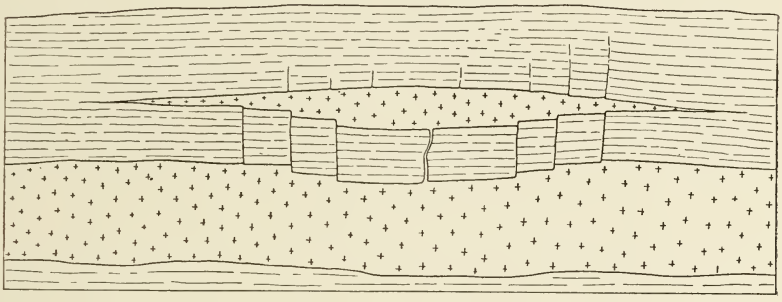

Fig. 60. Hypothetical section of batholithic intrusion with step-faulting

Such a mode of intrusion was suggested by Brögger in 1890 to account for the eruptions of igneous rocks in the Christiania region, which he imagined was at one time underlain by a magma basin, the roof of which became depressed by accumulating sediments, and was fractured and faulted, permitting magma to be pressed upward.[16] More or less circular areas of intrusive rocks with marginal zones of what appear to be the edges of successive intrusive sheets are common in this region, according to Brögger.

[15] Molengraaff, G. A. F. *Geology of the Transvaal*, 1904, 42.

[16] Brögger, W. C. Zeitsch. Kryst. Min., 16, 1890, 86.

Fractures may bound a batholith on one side, or on several, besides forming the top and bottom. Cross fractures may bound a side and cause strata to terminate abruptly against the intrusive body (Fig. 61). Fragments of wall rock of whatever kind may have been broken from the wall at the time when the major fracture ruptured the lithosphere, and such fragments entirely free, or attached at one end to the wall, may occur in any position within the intruded magma, or may be carried on through the channel by the flowing lava, according to the size of the fragments and the strength of the current, that is, its velocity.

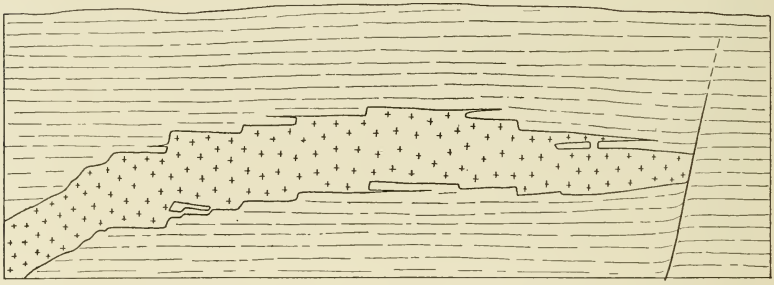

Fig. 61. Hypothetical section of batholithic intrusion with fragments of walls

A remarkable example of fragmentation and intrusion along the margin of a batholith is described by Whitman Cross as occurring in the West Needle Mountains, Colorado.[17] The batholith of granite is exposed over an area of forty square miles. Along its eastern border it is filled with fragments of hornblende-schist, which in places are angular blocks separated by veins and streaks of granite, well shown in the photograph (Fig. 62), in

[17] Cross, W. U. S. Geol. Survey, Atlas Folios, 131, 171.

FIG. 62. TWILIGHT GRANITE INTRUDED IN HORNBLENDE-SCHIST, ANIMAS CANYON, COLO.

W. Cross, U. S. Geol. Surv.

which it is seen that the white granite is beneath the blocks of dark-colored amphibolite, supporting them during the intrusion and solidification of the granite. A very large part of the fragmentation followed lines of schistosity, splitting hornblende-schist into thin plates, between which the white granite is intruded in thin layers with a gneissoid texture. The banded complex forms an enormous mass east of Animas Canyon, and is partly shown in the photograph (Fig. 63). The character of the intrusion is seen in Figure 64, which shows sharp-edged fragments of hornblende-schist, more or less displaced in the granite mass, and in places traversed by small veins of granitic pegmatite and aplite that penetrated the schist at the time of the granite intrusion, and have in this place remained undisturbed by shearing or fracturing since they solidified, although in other parts of the district they have undergone subsequent shearing and metamorphism. The case just cited is a good illustration of the intrusion of the magma of a batholith into highly fractured wall rock without evidences of solution of the fragments, or of sinking of a whole mountain of heavier fragments within the magma, which eventually crystallized into medium-grained granite, in places pegmatitic. Very similar phenomena are exhibited near the margins of batholiths in the Coast Range along the coast and islands between the Strait of Georgia and Queen Charlotte Sound in British Columbia, according to J. A. Bancroft.[18]

In this connection it is interesting to note an experiment by Lord Rayleigh, in which a leaden bullet was placed in a glass tube containing jelly, the bullet "somewhat nearly fitting" the tube. "After standing vertically for several days there was no appreciable descent of the

[18] Bancroft, J. A. Canada Dept. Mines, Mem. 23, 1913, 102-109.

bullet, and it required numerous longitudinal impacts against a suitable pad applied to the tube to bring the inertia into play and lower the bullet several inches.'"[19] The viscosity of the jelly hindered the descent of the lead bullet. Recognizing certain distinctions of definition and behavior between colloids and solutions, between solids and liquids, and between crystalline and amorphous matter, and at the same time remembering the physical inertness of rigid solutions, such as plate glass, and the physical mobility of liquid crystals, such as certain oleates, the bearing of the experiment cited on the possible behavior of solid rock fragments in viscous rock magmas is significant, and appears to be in accord with the common occurrence of blocks of wall rock enclosed in various parts of solidified molten magmas, and not accumulated at the bottom of intrusive masses.

The hydrostatic pressure of intruded magma against the walls of its conduits is so great that should any of the wall rock tend to spall off, through expansion from heating, it would, probably, be held firmly in place by the viscous magma. The absence of spalled slabs along the walls of dikes, sills, and laccoliths, militates against the assumption that such an operation takes place in other intrusions at greater depths under greater pressures. An intrusion of syenitic magma through dense porphyry near Laaven in the Christiania Fjord, according to Brögger, exerted such pressure against the wall rock that it produced internal shearing, with corresponding distortion and mechanical metamorphism of the porphyry.[20] However, the syenitic rock was partly crystallized, or was in the act of crystallizing, at the time

[19] Rayleigh. Proc. Roy. Soc., London, 1906, 486.

[20] Brögger, W. C. Zeitschr. Kryst. Min., 16, 1890, 101.

FIG. 63. TWILIGHT GRANITE INTRUDED IN HORNBLENDE-SCHIST, ANIMAS CANYON, COLO.

W. Cross, U. S. Geol. Surv.

of intrusion and exhibits shearing effects within its own mass, which show themselves in the shapes and arrangement of the crystals which form a medium-grained rock with gneissic texture.

A remarkable example of shearing in wall rock on both sides of a granite-pegmatite dike is shown in the photograph (Fig. 65), taken by A. E. Barlow, on Little Madawaska River, north of Berry's Bay, Ontario. The dike cuts granitic gneiss and amphibolite, between layers of which it has sent narrow offshoots. These bend in such a manner as to indicate a shearing of the two walls of the dike against the contents of the dike, but the large crystals of feldspar in the pegmatite show no signs of internal shearing or displacement.[21] A similar bending of gneissic layers against a body of unsheared granite-pegmatite has been described and illustrated by E. S. Bastin in his discussion of the pegmatites in Maine.[22]

It is possible to explain the form of irregularly shaped intrusions that have been called batholiths, when they are not merely conduits of volcanoes, or stocks, by the assumption that magma intruded itself into fractures which may have intersected one another at various angles, so that the walls of the intruded mass may have very irregular forms. This is also the conclusion reached by G. Steinmann with regard to the batholithic intrusions in the Andes.[23]

The walls that formerly fitted together, before being separated by the intrusion of magma, may be displaced by shearing as well as by the act of parting, the cause of fracture and parting being due to the stresses within

[21] Adams, F. D., and Barlow, A. E. Memoir 6, Department of Mines, Ottawa, 1910.

[22] Bastin, E. S. U. S. Geol. Survey, Bull. 445, 1911, 34.

[23] Steinmann, G. *Geol. Rundschau,* 1, 1910, 29.

that part of the lithosphere in which the batholith was formed, although the hydrostatic pressure of the molten magma may produce displacement to a greater or less extent, as in laccoliths, sills, and in some dikes in volcanic cones.

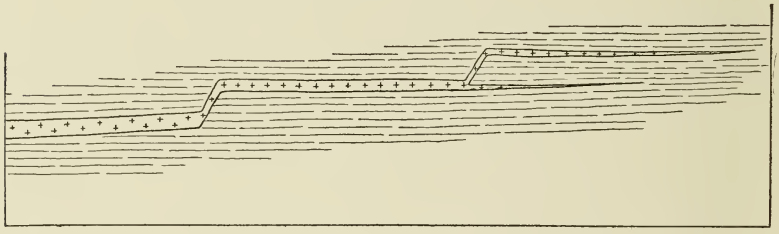

Fig. 66. Hypothetical section of intrusive sill

The material that once filled the space now occupied by an intruded body must exist in like volume elsewhere; either as one solid mass, as an aggregation of many solid masses, or as solidified matter which some have supposed was dissolved by the intruding magma, its volume not being appreciably lessened by solution and subsequent solidification. It seems to be more rational to assume that the displaced material was moved to one side at one time, as in the case of intrusion in dikes, sills, laccoliths, and bysmaliths, than to assume that this could not happen in the case of somewhat larger intrusions, merely because their position with respect to their wall rocks is not clearly visible. The fact that there are step-like angles on the upper walls or roof of a batholith, such as have been described for that at Marysville, Montana,[24] is in accord with the assumption that the intruded body occupies a fissure formed by intersecting fractures. A similar disposition of fractures is common

[24] Barrell, J. U. S. Geol. Survey, P. P. 57, 1907.

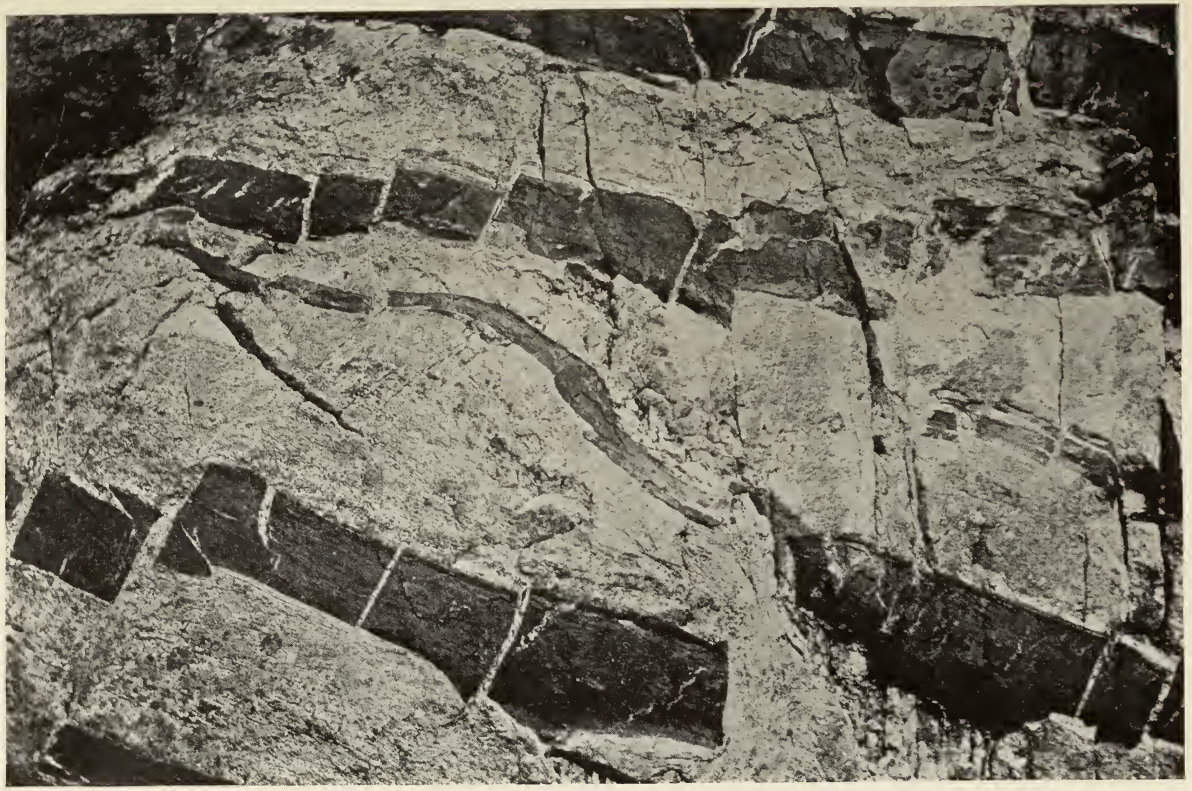

FIG. 64. TWILIGHT GRANITE WITH INCLUSIONS OF HORNBLENDE-SCHIST, ANIMAS CANYON, COLO.
E. Howe, U. S. Geol. Surv.

Fig. 65. Pegmatite dike cutting schists, Little Madawaska River, Ont.

A. E. Barlow

in sedimentary strata cut by sills or intrusive sheets which in places pass upward from one horizon to another (Fig. 66).

For the term batholith as originally used by Suess, with the modifications just discussed, which is the common usage among geologists, Professor R. A. Daly[25] has proposed to substitute the term chonolith, implying that the rock body has been molded by its containing walls, a characteristic which is shared with all other known bodies of intrusive rocks; and he relegates the name batholith to rock bodies which are supposed to have come into place by melting their way, or by overhead stoping. The term chonolith, if used, should be applied as a group name to all igneous intrusions, including batholiths, and new terms should be devised for any bodies that may be found to have worked their way into the lithosphere by solution, or by overhead stoping, if intrusions ever take place in these ways.

Intrusions of magma within stratified rocks which have inserted themselves along planes of weakness, usually within beds of shale, and have lifted the overlying strata in a dome-like arch, have been called laccoliths by G. K. Gilbert, and are easily recognized when well exposed in profiles that permit the arching strata to be clearly seen.[26] The occurrence of laccoliths in various stages of exposure in the Henry Mountains, Utah, has become classic through Gilbert's lucid descriptions, and a modified diagram of his ideal type drawn by Pirsson[27] is reproduced in Figure 67. Gilbert noted that

[25] Daly, R. A. Jour. Geol., 13, 1905, 485.

[26] Gilbert, G. K. U. S. Geol. Geogr. Survey, Rocky Mountains, Geology of the Henry Mountains, 1880.

[27] Pirsson, L. V. U. S. Geol. Survey, 18th Ann. Rep., part 3, chap. 6, 1898.

the height of these bodies is much less than their breadth, on the average about one-seventh as great, seldom one-third; that they occur at various horizons in the strata, and that some are separated by a nearly horizontal layer of shale into two or three parts; and also that in the Henry Mountains laccoliths are nearly circular domes.

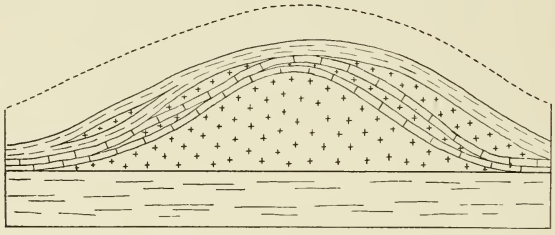

Fig. 67. Hypothetical section of a laccolith
L. V. Pirsson

Occurring as these do in nearly horizontal strata there can be little doubt that the arching of the roof was produced by the intrusive force of the magma, but the question arises why the overlying rocks should be lifted in a dome in the case of some intrusions and not in that of others within horizontal strata where only thin sills, or sheets of intrusive rocks, result. It is possible that in some laccolithic intrusions the overlying rocks may have been bent by thrusts that produced a general warping of the strata of the region, as in the Gallatin Mountains in the Yellowstone Park, and possibly in certain laccolithic intrusions in southwestern Colorado; and which was probably the case with some laccolithic intrusions in the Black Hills, South Dakota, according to T. A. Jaggar.[28]

[28] Jaggar, T. A. U. S. Geol. Survey, 21st Ann. Rep., part 3, 1901, 163.

A circular dome indicates a centralized force and a pipe-like conduit beneath the laccolith, which, however, has not been exposed or actually discovered beneath any of the Henry Mountain laccoliths. Magma spreading in a horizontal layer from a centralized conduit should heat the rock immediately over the conduit more than at the margin of the spreading sheet, producing some expansion of the roof and greater stress at this place. Moreover, the cooling of the magma in contact with the broad expanse of walls should increase its viscosity so that the effective pressure of the magma would be greatest at the center of the circular sheet, as suggested by Sidney Paige.[29] The rocks most commonly found in laccolithic bodies are the more siliceous kinds whose magmas are highly viscous as they approach the temperature of solidification. Such stiffening magmas would be slow to penetrate thin cool fractures and would tend to accumulate near the orifice of the conduit and in this way add to the stress upon the central portion of the roof. The pressure should be greatest at this place, and should decrease outward toward the margin of the sheet. If sufficient to overcome the weight of overlying rock, a dome-like arch should be produced. J. D. Dana called attention to the greater viscosity of the more siliceous magmas and suggested that this was the cause of the thickening of the intrusive sheet over the end of the conduit.[30] The possible process of laccolithic intrusion has been investigated experimentally by Ernest Howe with interesting results.[31]

However, many laccolithic intrusive bodies are not circular domes, but have elongated and unsymmetrical

[29] Paige, S. Jour. Geol., 21, 1913, 541.
[30] Dana, J. D. Am. Jour. Sci., 19, 1880, 24.
[31] Howe, E. U. S. Geol. Survey, 21st Ann. Rep., part 3, 1901, 291.

shapes, which have been described by Peale, Holmes, and Cross in Colorado. An interesting form of laccolith occurs in the Gallatin Mountains, Yellowstone National Park, and is represented diagrammatically in Figures 68 and 69. It illustrates the influence of regional flexures on the form of a laccolith, and also how unsymmetrical such an intrusive body may be. The conduit through which the magma flowed was inclined, undoubtedly, and rose southward from a synclinal fracture about ten miles to the north. The magma encountered the basal shales above the crystalline schists and beneath massive Paleozoic limestones; the shales splitting apart permitted the intrusion of the magma which moved southward and was divided into an upper and lower sheet by a thin wedge of shale and limestone which thickens southward, the wedge involving other strata between shale beds. The upper and lower sheets of intruded magma thin out within a distance of several miles.[32]

Where the magma entered the shale belt it arched the overlying Paleozoic strata and became about a thousand feet thick, the width of the intruded body at this place being about 13,000 feet. It solidified into fine-grained andesite-porphyry, a rock of intermediate composition. The base of the laccolith is well exposed in places and is almost horizontal. The limestone roof has been partly removed by erosion, but where still preserved at its contact with the igneous rock it exhibits almost no evidence of mineral alteration, and is traversed by innumerable small, nearly vertical fractures, showing that the brittle limestone was minutely ruptured in the process of flexure, and did not bend as a plastic mass.

In the same mountains there are many thin intrusive

[32] Hague, A., Iddings, J. P., et alii. U. S. Geol. Survey, Mon. 32, part 2, 1899, 60.

FIG. 68. SECTION OF THE GALLATIN MOUNTAINS, YELLOWSTONE NATIONAL PARK, SHOWING FORMS OF INTRUSIVE BODIES AND THEIR RELATION TO BLOCK-FAULTING

FIG. 69. INDIAN CREEK LACCOLITH

sheets of similar magmas which have penetrated Jurassic and Cretaceous shales, and although in horizons from 3,000 to 10,000 feet higher than that in which the Indian Creek laccolith occurs, they have not caused an appreciable arching of the overlying strata, but appear to be sills with nearly constant thickness, thinning out very gradually. Their intrusion undoubtedly took place along the edges of the strata where they were intersected by conduits of magma connected with the profound synclinal fracture situated to the north, where the block of these stratified and underlying rocks is faulted against a block of crystalline schists forming Sheep Mountain and the mountains north of it. The intrusion of the many thin sheets probably followed a splitting of the stratified formation in consequence of the thrusting together of the two blocks just mentioned. We may imagine that the lifting of the superincumbent strata at the time of these intrusions was not due wholly to the hydrostatic pressure of the magma, but was in part a result of the separation of the more rigid strata of sandstone and limestone by thrusting, just as sheets of paper may be made to separate by a warping thrust. The same suggestion has been made in explanation of the intrusion of the Whin Sill in Northumberland.

Arching strata crack, and according to the disposition of the load, the consistency of the rocks, the localization of the pressure of the intruded viscous magma, and the possible existence of previous fractures, the bending strata may become displaced or faulted to a greater or less extent, and in various ways.

The fracturing of a circular dome supporting a heavy load should take place in nearly concentric arcs; and, if the intrusive force of the magma is sufficient, a nearly circular segment of the roof of a laccolith may be dis-

placed. Where a dome-like roof is not so heavily loaded it may fracture radially, as described by H. H. Robinson in the case of the laccolith of Marble Hill, near San Francisco Mountain, Arizona.[33] If fracturing is more complete or extensive in one part of a dome than in another, displacement of the roof may be unsymmetrical as in some of the faulted laccoliths in Colorado, described by Cross,[34] such as that of Mount Marcellina (Fig. 70), an ideal section through which is shown in Figure 71.

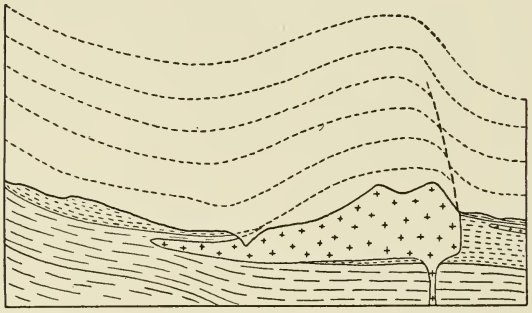

Fig. 71. Hypothetical section of Mount Marcellina laccolith

W. Cross

Cross calls attention to the fact that in Colorado, sills and laccolithic intrusions of magmas having various compositions occur at all horizons throughout Paleozoic and Mesozoic strata and are not distributed in any order according to densities. Since both heavier and lighter magmas erupt with force enough to eject millions of tons of lava on to the surface of the earth, their ability to intrude themselves into fissures and lift very consider-

[33] Robinson, H. H. U. S. Geol. Survey, Prof. Paper 76, 1913, 70.

[34] Cross, W. U. S. Geol. Survey, 14th Ann. Rep., part 2, 1893, 165.

FIG. 70. MOUNT MARCELLINA, COLO.

W. Cross, U. S. Geol. Surv.

able masses of rock does not seem to be a matter of the relative densities of the lavas, the differences between the densities of which are comparatively slight.

Concentric fractures in a dome-like roof above a laccolithic intrusion of magma may lead to a somewhat cylindrical faulting of the overlying rocks, which may be lifted to a greater or less distance according to the resistance it offers to the intrusive force of the magma.

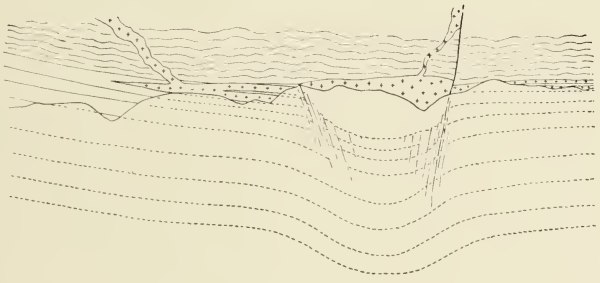

Fig. 72. Hypothetical section of Mount Holmes bysmalith

Since, as Van Hise states, the fractures in an anticlinal fold commonly dip from above outward, arcuate fractures in a dome should produce more or less concentric conical segments pointing upward. Resistance to the hydrostatic pressure of a lifting magma varies with the area of the surface exposed to it and with the mass of the overlying block of rock, so it is quite possible for a dome-like roof under favorable conditions to be forced upward sufficiently to produce a plug-like body of igneous rock, or a bysmalith. Bodies of this character occur in the Gallatin Mountains, Yellowstone National Park, associated with laccoliths and sills[35] (Fig. 72).

[35] *Loc. cit.*, p. 16.

They may be considered to be modifications of laccoliths, into which they should grade according to the amount of displacement of the faulted roof.

If a magma were intruded under very great pressure, that is, at considerable depth within the lithosphere, where the surrounding rocks may have been considerably heated before the intrusion, a dome-like deformation of the roof over the intruded magma might take place with the production of schistosity parallel to the sides of the intruded mass, as is the case with the granitic intrusion in the Black Hills, South Dakota, described by Sidney Paige and others. If subsequently the pressure of the magma were lessened, either by the contraction of the magma through partial crystallization, or by reason of the yielding of the retaining walls through rupture, the sheared and fractured roof might settle sufficiently to permit the intrusion of uncrystallized portions of the magma into fractures which might occur in planes of schistosity, or irregularly in the roof-rock, producing aplitic and pegmatitic veins, or larger apophyses of the main body of magma.

As already pointed out, thin sheets or sills of intruded magma commonly occur along beds of shale between more resistant beds of limestone or sandstone in such a manner in some regions as to indicate that they intruded themselves into fractures caused by the splitting of the shale beds at the time of flexure and thrusting of the whole block of dislocated strata. An example of this mode of intrusion is to be found in the sills intercalated in the strata of Electric Peak, in the Yellowstone Park (Fig. 73).

In other cases, as in the region of the great stock-like intrusion in the Crazy Mountains, Montana, which is a body of coarse-grained rocks eight miles in diameter,

Fig. 73. Intrusive sills in Electric Peak, Yellowstone National Park

J. P. Iddings, U. S. Geol. Surv.

the surrounding Tertiary shales and sandstones are traversed by innumerable thin sills of andesite-porphyry that extend outward from the central mass. The strata and intercalated sills are cut by many dikes of similar porphyry that radiate in all directions from the stock. The sedimentary strata rise up from the surrounding region toward the intrusive core, and the sills and dikes fill the fractures that must have accompanied such a dislocation of nearly horizontal beds, and occupy the space that such displacement involves. Since the Tertiary formations were not far from the earth's surface at the time of magmatic intrusion, their weight could not have been very great, and the intrusion of sills may have taken place during the early stages of eruption, when the magma was working its way through the uppermost rocks and may have been capable of producing laccolithic doming.

However, the broad zone of contact metamorphism surrounding the core of coarse-grained rocks of the Crazy Mountains, and the composite character of the core with its intersecting bodies of different rocks, indicate that the central intrusive body, or core, is more like a stock, or the conduit of a large volcano, than like a laccolith or bysmalith, around which there is commonly little or no metamorphism of the wall rocks. So that it is possible that a great cone of surface lavas and tuffs covered this region, and that the hydrostatic pressure of a magma column in the conduit beneath the crater may have caused the intrusion of the magma into the fissile shales beneath the surface lavas. As is easily understood, sills usually thin out toward their forward edge, and may pass up into higher horizons of strata where a cross fracture opens the way. The Whin Sill is known to rise in this manner from one horizon to another

for an altitude of 1,650 feet. Less commonly a sill may pass downward to a lower horizon.

While magmatic intrusions along horizontal or nearly horizontal fractures are called sills, most of those along vertical or highly inclined fractures are called dikes, and when branching or rather narrow are sometimes called veins. However, the distinction between dikes and sills is something more than one of angular position, for intrusions along bedding planes of stratified rocks are commonly called sills at whatever angle they may be tilted, and intrusions in fractures that transgress stratified beds are usually classed as dikes. In general, the former and almost all nearly horizontal fractures have been produced by thrusts, while the more nearly vertical fractures commonly result from tensional stress, though not always. A good illustration of parallel dikes that are not vertical is shown in the photograph (Fig 74), taken by F. L. Ransome. The dikes are of pitchstone, and traverse massive andesite on Toroda Creek, Washington.

Tensional fractures are usually straight, and often occur in parallel systems traversing various formations for long distances in some regions, as in Northwestern England and Scotland, where two nearly parallel dikes extend for at least sixty miles, and similar systems of dikes occur over an area of about 40,000 square miles.[36] Parallel dikes may be comparatively close together, or far apart. They may have been formed at one time, and consist of similar rocks, or they may have been produced by successive fractures which admitted different kinds of magmas that were intruded at different epochs of

[36] Geikie, A. *The Ancient Volcanoes of Great Britain*, London, 1897, vol. I, 80.

FIG. 74. PARALLEL DIKES OF PITCHSTONE IN ANDESITE, TORODA CREEK, WASH.

F. L. Ransome

eruptive activity. Their trend may be nearly straight for long distances, or it may be irregularly curved.

Dikes having like trend, and resulting from the same fracture, may not be exposed continuously at the earth's surface, for as fractures may terminate at various distances in the direction of their length, they may also terminate at various altitudes within the lithosphere, and this irregularly throughout their length, so that a very long dike may fail to reach the same stratigraphic horizon in all parts of its length. A notable example of such a dike is the great Cleveland dike in the north of England, which has been traced for 110 miles, and may be continuous with dikes that extend eighty miles farther, into Scotland. It fails to reach the surface for long distances, and is known to rise through more than 17,000 feet of strata, thinning out vertically.[37]

Very long fractures due to synclinal flexure, in some instances, may proceed with great slowness, advancing spasmodically both lengthwise and vertically, so that intrusions of magma may progress interruptedly through them, appearing at different times in new districts along the line of the trend of the fractures. This appears to have happened in the volcanic outbreaks in the Hawaiian Islands, the older eruptions having been situated to the northwest of the modern ones, as pointed out by Dana.[38]

A fan-like arrangement of fractures, and consequently of dikes, may arise from an unsymmetrical flexure or warping of strata, or of a more homogeneous mass of rock, as demonstrated by Daubrée.[39] Such a case is illustrated by the group of divergent dikes at the east base of Electric Peak, Yellowstone National Park, where

[37] Geikie, A. *Loc. cit.*, vol. II, 142.
[38] Dana, J. D. *Characteristics of Volcanoes,* New York, 1890.
[39] Daubrée, A. *Études Synthétiques,* Paris, 1879, 310.

Cretaceous strata have been bent up sharply, and where, subsequently, a profound fault was accompanied by a vertical displacement of over 6,000 feet. Radiating dikes may also result from the tension produced in the circular wall of a conduit within the cone of a volcano by the hydrostatic pressure of the column of lava; and may also be produced by tension in the dome-like roof of a laccolithic intrusion. The case is illustrated by the radiating dikes about the stock in the Crazy Mountains, already mentioned. The expansion of the walls by the pressure of the lava, as well as that due to the intrusion of lateral sills, causes the walls to split in nearly vertical cracks that extend outward from the conduit. In the course of time dikes may radiate on all sides of the cone, being more numerous in places where the resistance was least, owing to the character of the rocks, whether tuffaceous or massive, and according to the structure and dimensions of the cone, or dome. Radial fissures appear from time to time on the slopes of Mount Etna, and lava issues from them at various places where it finds the freest exit. In the denuded volcano of Crandall Basin, Wyoming, there are dikes radiating from the conduit which are more numerous on the southwest side, where the volcanic breccia and tuff was deepest, over the sloping surface of limestone rocks that rose higher on the northeast side of the volcano.

Fractures intersect one another in some instances, even when they belong to the same system, or group (Fig. 75). They may have been produced by the same set of stresses, or by successive ones. So dikes intersect other dikes as they extend outward from a volcanic vent, or traverse a region without connection with a volcanic cone. Intersecting fractures, when contemporaneous, may break the wall rock at the line of their intersection

FIG. 75. MULTIPLE DIKES, STONEHAM, MAINE

E. S. Bastin, U. S. Geol. Surv.

into comparatively small fragments, or a shearing stress may crack rocks into small pieces along a fracture plane (Fig. 50), so that magma may be able to carry up the fragments, and thus open a larger channel for its passage than exists within the narrower fissures. This may lead to the localizing of the flow in such a place, since a thicker column of magma would remain hotter and more fluid than a thinner sheet.

Explosions of expanding gases might still further shatter the edges of projecting wall rocks between converging fractures, enlarging the conduit from time to time. This may have taken place at the focus of the fan-shaped group of fractures at Electric Peak, where a stock of diorite and granite-porphyry occupies the conduit of an ancient volcano, whose extruded lavas and breccias have been partly preserved in Sepulchre Mountain. Explosions may take place in magma that is rising in a fissure as it approaches the surface of the earth, where the weight of the overlying load may be insufficient to suppress the gases, or where the magma may encounter strata rich in water, which would become superheated by the molten magma. This might result in widening the fissure and possibly in forming a pipe or funnel-shaped opening spreading toward the surface. Daubrée has demonstrated the power of exploding gas to drill a pipe-like channel through apparently solid granite, at the same time polishing and grooving the walls by the attrition of the particles driven through it.[40]

Funnel-like conduits abound in the Kimberley district in South Africa, according to Du Toit.[41] They are associated with dikes of diamond-bearing basaltic lavas, and

[40] Daubrée, A. *Études Synthétiques,* Paris, 1879, 669.

[41] Du Toit, A. L. Geol. Com. Cape of Good Hope, 11th Ann. Rep., 1907, 135.

in some instances have been traced downward into dikes, as in the St. Augustine mine, near Kimberley, a section through which is shown in Figure 76. The widened fissure appears at a depth of 800 feet. It passes up into

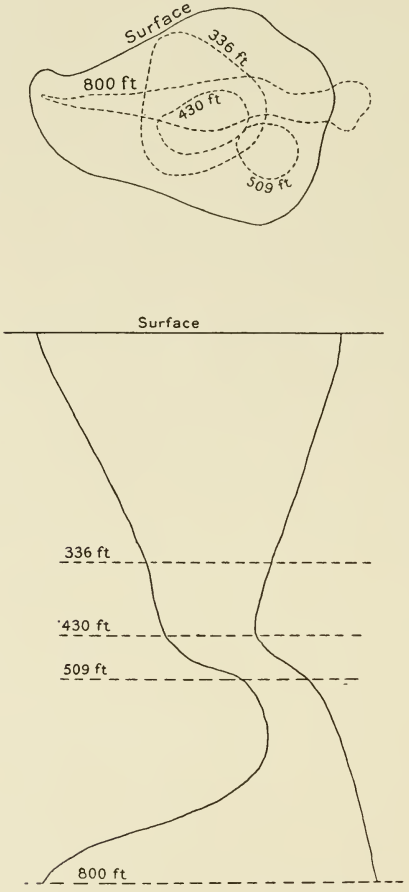

Fig. 76.

Section of St. Augustine Mine, near Kimberley, South Africa
A. L. Du Toit

a narrow circular vent, and where the gases probably began to find less resistance the aperture expanded, forming a crooked channel up to 430 feet, above which the opening enlarged considerably.

Such explosions must scatter fragments of wall rocks, as well as tuff and lava, over the surface of the ground, and build a volcanic cone, whose size will depend on the violence and length of eruptive activity. Long-continued action, through centuries, should enlarge the conduit as it piles up a great volcano. When eruptive activity ceases and the lava within the conduit solidifies, there should remain a stock of igneous rock, which may be a large, nearly homogeneous body, if the last eruption was violent and much lava flowed out; or it may be a body, variable in composition, intersected by smaller bodies of other rocks which were the last eruptions of waning activity, indicating that there was a gradual decrease in activity, and that the final eruptions took place after long periods of inactivity, during which the magma within the conduit had had time to differentiate into diverse kinds of lava. The first case seems to be illustrated by the volcanic core at Haystack Mountain, Montana, where there are few, if any, intersecting bodies within the core; the second, by the cores at Electric Peak and at Crandall Basin, and by that in the Crazy Mountains.

In general, it may be said that where the wall rocks around intrusive bodies exhibit much metamorphism, there much lava has flowed by, and it may be concluded that the altered rocks were the walls of conduits through which lava flowed for long periods of time. For if the metamorphism observed in the walls of conduits of volcanic mountains that acquired great size required the heating effects of centuries of contact with molten lavas,

it is not to be expected that similar changes can be induced in wall rocks of like composition by bodies of magma commensurate in size to those forming stocks, if these magmas came to rest at the first intrusion, unless they possessed an excess of heat equivalent to the relays of heat given off by countless fresh intrusions of molten lava that pass through the throat of an active volcano. It must be remembered, however, that the original character of the rocks forming the walls of volcanic conduits is a fundamental factor in the kind, as well as in the apparent extent, of metamorphism produced by contact with molten magmas.

In conclusion, it may be said, as J. D. Irving has stated with respect to the intrusive bodies in the Black Hills of South Dakota, that the manner of fracturing of the rocks into which magmas have been intruded has been almost without exception the factor which has determined the form assumed by the intruded bodies.[42]

[42] Irving, J. D. Ann. New York Acad. Sci., 12, No. 8, December 18, 1899.

CHAPTER VIII

EXTRUSION OF LAVAS UPON THE EARTH'S SURFACE

Molten magmas that reach the earth's surface as volcanic lavas issue from orifices and fissures in the uppermost rocks, which are continuous with fractures occupied by intruded magmas at greater depths. Their manner of emergence differs greatly in different instances, as do also the location of their outbreaks and the material of which the lavas are composed. Upon passing from conduits to the open atmosphere, magmas do not change their physical characteristics to any great extent, but they enter a new physical environment. Instead of being surrounded by confining walls, they have nothing to restrain their movement but atmospheric gases and the irregularities of the ground over which they flow. There is a change of pressure, which, within an open conduit shortly before lavas reach an outlet, is chiefly the weight of the upper part of the lava column; while within a closed conduit, either in the act of opening for the first time, or closed by solidified magma in its upper part, the pressure is the weight of the lava plus the vapor pressure of whatever gases may be free to expand.

In the case of lavas emerging from fissures on the flanks of a volcanic cone, there may be the pressure of the lava column within the cone that is higher than the point of emergence of the lava. As lava reaches the

atmosphere, the vapor pressure of the dissolved gases is only offset by the pressure of the atmosphere. However, it is only the gases in the surface layer of lava exposed to the atmosphere that have this opposing pressure; gases within deeper layers of lava, as at the bottom of a flow, have the weight of the overlying lava upon them. This change of pressure upon the extrusion of molten magma is of great moment in its behavior, and will be discussed at some length later on.

There is also a change of temperature upon the eruption of lava from its conduit, which is often very pronounced. Within a conduit, lava is in contact with wall rocks whose temperature depends upon the rock temperature before fracture and the intrusion of molten magma, and upon the length of time magma has been in contact with the wall rocks, and also upon the temperature of the magma. Owing to the poor heat-conductivity of rocks, as well as of magma, that part of the wall rock which is near the contact with the magma soon attains a temperature nearly equal to that of the magma in contact with it, although the rocks at great distances from the magma heat very slowly. The magma in contact with the wall rocks will cool somewhat from loss of heat and poor conductivity, and will become more viscous than the hotter middle portion of the magma within the conduit, which will flow more rapidly than the marginal portions that may remain sticking to the walls, unless subsequently heated by continued flow of hotter magma. Consequently, lavas erupted at the earth's surface may reach it at temperatures quite as high as those under which the magmas existed in deep-seated reservoirs. Indeed, it is possible that the temperatures of magmas in the uppermost parts of their conduits, in some instances, may be higher than those of the same magmas

when much lower down, owing to chemical reactions between liberated gases.

The temperature of the atmosphere being far below that of molten lavas, although gases are poorer conductors of heat than solids are, convection currents within the atmosphere rush great volumes of cooling gases over the surface of exposed lavas, from which heat is also radiating. Quickly a rock crust forms on the liquid lava and acts as a blanket to hinder the further rapid loss of heat, which must be conducted slowly through the covering of rock. The chief effects of sudden cooling of lavas are changes in viscosity and in the rate of solidification, with attendant modifications in the forms of extruded bodies of lava, and in the extent and modes of crystallization in the resulting rocks.

As to the manner in which lavas reach the earth's surface, there may be fissure-like openings where fracture-planes cut through upper rocks which are like open dikes, and there may be explosion channels connected with fracture-planes at depths where the gases within magmas are able to overcome surrounding pressures, or where magmas encounter water-charged strata and produce gas at sufficient tension to cause repeated explosions. It is known that where lava reaches the surface through a fissure it flows from long stretches of the opening in a comparatively quiet stream, and at certain points it may rush forth with more or less violent ebullition of gas, and at these places the outflow may continue longer than from other parts of the fissure. This appears to have been the case with the great fissure eruption in Iceland in 1783, small cones being built up at many points along the fissure. Similar parasitic cones occur on recent lava flows near the Idaho-Oregon

boundary, according to I. C. Russell.[1] It takes place to a less extent in fissure eruptions on the flanks of Etna and at other volcanoes, forming subsidiary cones.

Where fissures reach the surface in comparatively level country, or in valley basins, floods of lava may conceal the fissures through which they poured, as in the region of the Yellowstone Park, where immense floods of rhyolite covered depressions of the basin into which they flowed, as well as the foothills of surrounding mountains. The same is true of the vast plains of basalt in the Snake River valley in Idaho, and elsewhere. In the Bonanza Basin near Cornucopia, in the Blue Mountain region in Oregon, basalt sheets, which have accumulated to a thickness of 2,000 feet, appear to have flowed from fissures that are now occupied by dikes exposed in the neighboring mountains. In the northern Cascade region along the Teanaway River there are several thousand feet of lava flows which in places are traceable to dikes beneath them, which are seen cutting underlying strata.[2] In some instances such fissure eruptions have been accompanied by gaseous explosions that have covered the surrounding country with tuffs which were immediately overflowed by sheets of lava, as is well shown on Mount Evarts in the Yellowstone Park, where the ancient surface of limestone country is overlaid by rhyolitic tuff covered by massive rhyolite continuous with the plateau sheet. A similar sequence of tuffs and massive flows of rhyolite occurs in the San Juan Mountains, Colorado (Fig. 77), as described by Cross.[3] The Eureka rhyolite in the Animas Valley is in places 2,000 feet thick. Similar flows of basaltic lavas

[1] Russell, I. C. U. S. Geol. Survey, Bull. 217, 1903.
[2] Smith, G. O., and Calkins, F. C. U. S. Geol. Survey, Atlas Folio, 139.
[3] Cross, W. U. S. Geol. Survey, Atlas Folios, 57 and 120.

Fig. 77. Rhyolite flows above San Juan tuff, between Virginius and Marshall Basins, Colo.

W. Cross, U. S. Geol. Surv.

and tuffs have been noted in the northern Cascade Mountains, and in many other places. In the canyon of the Deschutes River, Oregon, rhyolitic tuffs are topped by a sheet of basalt, and in the Yellowstone National Park flows of basalt and of rhyolite are intercalated with one another.

In the case of localized volcanic cones it is not necessary that a fissure-like conduit, or a recognizable fault line should be visible beyond the area covered by tuffs and extruded lavas. Conical volcanoes are built up largely of explosive material, and explosions may open a channel for a body of rising magma before the fracture through which it is rising reaches the earth's surface, as is so well illustrated by the funnel-shaped pipes of diamond-bearing lavas in South Africa, and which may be the case with the volcanic necks or pipes filled with agglomerate in the region of the Firth of Forth near Edinburgh, described by Sir Archibald Geikie.[4]

It is commonly true, however, that volcanoes and volcanic vents are situated along lines corresponding to planes of fracture, or of structural weakness in the lithosphere, but the actual point of egress through the uppermost rocks may have been determined by local conditions that fixed the direction of fracture in stratified formations. Thus magma may have flowed through fractures that were parallel to planes of stratification until it had approached so near to the surface that the vapor tension of its gases, or of those generated in adjoining rocks, was sufficient to explode a way directly through overlying rocks. The volcanic masses of Central France, according to Michel-Lévy, occur at a sharp bend of the hercynian fold, and probably rose through

[4] Geikie, A. *The Ancient Volcanoes of Great Britain,* London, 1897, vol. 1, 427.

gaping fractures occasioned by depressions of one side of this fold, following the alpine elevation of the other.[5]

In most instances modern active volcanoes cover wide areas of the earth's surface and obscure the structural features of the pre-existing rocks. Greatly eroded or dissected volcanoes permit the structure of underlying formations to be seen when they have been cut deep enough. In the excellent example at Electric Peak and

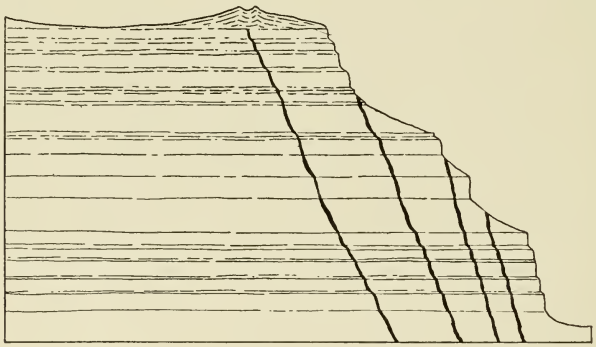

Fig. 78. Cinder cone and dikes, Grand Canyon of the Colorado

C. E. Dutton

Sepulchre Mountain, in the Yellowstone Park, the connection between volcanic conduit and fractured strata is well shown. In the denuded volcano of Haystack Mountain, Montana, a connection with fractures and dislocations is also obvious. In the deeply eroded region of the Grand Canyon of the Colorado a small basaltic cone has been cut across by a vertical cliff, and a dike of basalt is seen extending up to the center of the cone, according to Dutton (Fig. 78). In the Auckland region, New Zealand, a volcanic cone is situated on the edge of

[5] Michel-Lévy, A. Bull. Soc. Géol., France, 19, 1889-1890, 695.

Fig. 79. Bromo and other cones in Tengger Crater, Java

a cliff directly on the line of a fracture and displacement of Tertiary strata, according to Heapy. In Owens Valley, California, according to A. Knopf, small basaltic cinder cones occur along fault lines at the eastern base of the Sierra Nevada escarpment, and have been faulted in places by recent dislocations along the same lines. The Quarternary volcanoes of Mono Lake valley, in California, as Russell has pointed out, are situated on lines of fracture which are a part of the great Sierra Nevada displacement, along which recent movements have taken place. These volcanoes are in part cones of rhyolitic tuff, with outflows of obsidian which form short coulées several hundred feet thick at their extremities; other cones and flows are andesitic and basaltic. James Geikie has well said: "It is not the configuration of the surface, which may be mountainous and lofty, or low-lying and plain-like, but the presence of suitable lines of fracture that determines the appearance of volcanoes."[6]

Owing to the great length of time that usually elapses between the inception of extrusive activity of a volcano and its complete extinction, it is not possible to give an account of what might be called the life history of any one volcanic cone. Thus the much eroded ancient crater of Aso volcano in Kyushu, Japan, which is drained by two semicircular river channels, has a central mountain mass upon which there are at present several active craters; and the floor of the great crater of the Tengger volcano, in Java, is a sand-plain from which rises a group of younger cones and craters, the most active of which is the Bromo, which is shown with its companions in Figure 79; the highest active volcano in Java, Semeru, is seen in the distance to the south.

[6] Geikie, James. *Mountains,* Edinburgh, 1913, 236.

It is true, that eruptions have broken forth in particular localities within historic times and have produced cones of tuff without flows of lava, and have ceased all apparent activity, such as the eruption of Monte Nuovo in the Phlegræan Plain, near Naples, in 1538; but experience with other volcanoes has shown that cessation of activity is not necessarily extinction, for volcanoes like Vesuvius have been inactive for centuries, and have resumed activity; so that it is not possible to determine when a modern volcano becomes extinct. Fuji Yama (Fig. 80) has not been in eruption for over two hundred years, but it would not be wise to assume that it is extinct. It may at any moment renew its activity. An apparently extinct modern volcano may be found in El Tronador in Argentina (Fig. 81), since erosion has destroyed its conical summit. When ancient volcanoes have come to an end, and have been eroded and cut in two by faulting, it is possible to assert that in their cases volcanic activity has ceased.

From the appearance of new volcanoes in historic times, from the behavior of active ones, together with the exposures of dissected ancient cones, it is possible to present an epitome of the life history of volcanic action at a single orifice that may portray the principal features in the birth, life, and death of a volcano; it being understood that there may be infinite variety in the experience of volcanoes in different localities. Of the few descriptions of the birth of new volcanoes, those of Jorullo in Mexico, in 1759, of Izalco in San Salvador, in 1770, and of Monte Nuovo in the Phlegræan Plain in Italy, in 1538, are the most graphic. In each case the outbreak took place in regions of active volcanism, and was not the commencement of volcanic activity within the region as a whole, but was the eruption of lava from

Fig. 80. Fuji-Yama

a new orifice. In each case eruption at the earth's surface was preceded by subterranean noises and earthquakes that continued intermittently and with increasing intensity for several months. Then, in the case of Izalco, the ground opened up and emitted lava, "fire," and "smoke"; later on lava flows ceased and were followed by ejections of vast quantities of dust, lapilli, and stones, which formed a cone that has reached a height of about 3,000 feet. No lava has been erupted in recent years, but activity is continuous, with mild explosions every quarter of an hour. At Jorullo, the ground appeared to rise up in several places, from which eruptions took place simultaneously. The swelling up of the ground into small hills at the time of the outbreak of lava is quite in accordance with the possibility of a mild form of laccolithic intrusion near the earth's surface, followed by the cracking and explosion of the roof, and the welling up of lava between the fragments, and is a slight support for the ancient theory of cones of elevation. Where the earliest eruptions were highly explosive, as was the case with the Tertiary volcanoes in the region of the Yellowstone Park, much fragmental material from the previous surface rocks occurs with the volcanic tuffs and breccias at the base of the accumulations, which contain very few flows of massive lava.

The subterranean noises and earthquakes that precede the first outbreaks of lava at the earth's surface, and in some instances continue for months, testify to the gradual rupturing of rocks above the rising magma and the comparative slowness of the process of blasting its way upwards. Moreover, it shows that rupture may proceed from horizon to horizon below the surface without affecting the uppermost rocks until they are finally reached; in some instances by gaping cracks; in

others, by irregularly distributed fractures and upheavals; in others, by violent explosive fragmentation. In the three cases just cited no considerable faulting or dislocation of the uppermost rocks has been recorded, but in that of the cinder cone on the edge of a cliff near Auckland, New Zealand, already referred to, eruption took place on a line of fracture toward which the Tertiary strata dip from both sides beneath the volcanic cone.

The length of life of a volcano is a matter of great interest and significance, and is a very considerable element in the problem of the cause and nature of volcanic activity. In previous discussions, we have been concerned chiefly with the causes of the initiation of volcanism, but the question that now arises is, Why should there be only one comparatively short period of volcanic activity at one orifice, or terminus of a conduit; at another, somewhat longer action, with periodic outbreaks during a moderately long time, while in other places, volcanic activity has continued for centuries and has built up gigantic cones?

Small volcanic cones, such as Monte Nuovo, or Monte Gimilaro on the slopes of Etna, or the miniature cones described by Gilbert in Utah, are subsidiary eruptions in large volcanic regions; and in the case of Monte Gimilaro, a small cinder cone with lava flow that formed in 1886, eruption undoubtedly resulted from a rupture and displacement of rocks under stresses that were promptly adjusted after the outflow of a small amount of lava, which soon solidified and closed the fissure. In this particular case, the source of magma was the neighboring conduit of the volcano, and although lava may never flow from the cone of Gimilaro again, the greater volcano, Etna, continues indefinitely. In the

FIG. 81. EL TRONADOR, ARGENTINA

Bailey Willis

case of Monte Nuovo, however, the nearest active volcano, Vesuvius, is more distant, and its lavas are quite different in composition from those of the smaller transient volcano. It is probable that the leucitic lavas of Vesuvius and the trachytic lavas of Monte Nuovo came from differentiated portions of some common magma that occupies a subsidiary reservoir at considerable depth.

Why do Etna and Vesuvius continue to erupt lavas intermittently in well-established craters, and build up mountains thousands of feet in altitude? and why do Stromboli and Kilauea continue even more regularly and more quietly to maintain columns of molten lava which is liquid within the craters at the summits of their conduits?

At Vesuvius explosive action is much more frequent and pronounced than at Etna, in its present stage, and has blown off the top of the cone more than once in historic times. Eruptions of lava from lateral fissures also occur, but not so frequently or so voluminously as at Etna, where there are hundreds of parasitic cones, which are unknown on the slopes of Vesuvius. At Kilauea explosive eruptions from the crater are almost unknown, certainly none of any considerable magnitude, but lateral eruptions of non-explosive lava frequently break out upon its slopes, and also on those of Mauna Loa; however, parasitic cones are rarely formed. At Stromboli the action of the lava is still less violent; there is constant boiling with small explosions of lava bubbles, the lava seldom breaking through the walls of the cone.

The lavas of these volcanoes are all basaltic, though somewhat different in composition. The lavas of the Hawaiian volcanoes appear to be the most liquid, those

of Vesuvius the least so of the four craters named. As to their relative sizes, Stromboli is comparatively small, Vesuvius somewhat larger, Etna a great volcano over 10,000 feet in height, Kilauea and Mauna Loa much greater than Etna when their altitude above the ocean bottom, from which they rise, is taken into account. To their altitudes of 4,000 and 14,000 feet above sea level must be added 15,000 feet of ocean depth, making their heights as volcanic cones 19,000 and 29,000 feet respectively.

It is self-evident that a large initial outflow of lava, which may form a relatively large conduit of molten magma, may establish a lava column so large that it should require a very long time to cool to a solidifying temperature. Moreover, the flow of a large volume of magma through a conduit should heat the walls to a higher temperature, and the wall rocks to a greater distance from the conduit, than shorter flows of smaller volumes, of possibly cooler magma, would heat them. Consequently, a larger or more violent initial eruption should establish a longer-lived volcano, other things being equal.

If the supply of lava depends chiefly on the dynamical movement of the rocks in a neighboring region, such as the depression of the roof of a subsidiary reservoir, or perhaps on the dynamical equilibrium within a very large part of the underlying lithosphere, then it may happen that very great eruptions may terminate in a comparatively short period of time because of the adjustment of deep-seated parts of the dislocated lithosphere. This is undoubtedly the case with some great fissure eruptions, such as those of the plateau rhyolites in the Yellowstone Park, and it may have been the case with some great intrusions of large bodies of magma that seem to have

FIG. 82. WALL OF CRATER OF SOUFRIÈRE, ST. VINCENT

E. O. Hovey, Am. Mus. Nat. Hist.

been almost isolated dynamic acts of great magnitude, such as the intrusion of quartz-diorite in Argentina previously referred to. If, however, volcanic activity at certain centers continues for extremely long periods of time without evidence of considerable dynamical movements in neighboring rocks, or in underlying parts of the lithosphere, and without the ejection of great volumes of lava, the question arises, How is this activity maintained for such long periods, and why does it eventually cease?

The most impressive fact about the maintenance of an open crater of liquid lava for centuries, such as that of Kilauea (Fig. 7), is its equilibrium with the atmosphere. If continuous connection is maintained with deep-seated reservoirs, as we may assume it has been, the pressure of the walls of the conduit and reservoir upon the magma in all its ramifications can not be more than sufficient to counterbalance the pressure exerted by the lava itself, and the friction involved in its flow through its channel. Rock matter is denser than molten magmas having about the same composition, but rocks possess a degree of rigidity that must in large part compensate for the differences in weight in the equation of equilibrium, whatever its expression.

From such conduits, relatively small volumes of lava escape from time to time; it may be through fissures in the cone of the volcano, or into fissures in wall rocks lower down; it may be over the rim of the crater in flows that follow depressions and drainage channels on the slopes of the cone; or as ejected lumps, or as dust from exploded pumice; in this way building up a heterogeneous mountain whose structure is well illustrated by the photograph taken by E. O. Hovey, of the wall of the crater of Soufrière, on St. Vincent (Fig. 82). After

the escape of lava through lateral fissures, or over the rim of a crater, the magma within the conduit usually settles down to greater or less depths within it, as is commonly noted at Kilauea, and subsequently rises slowly prior to another outbreak, or period of special activity. This slow accession and ascension of lava within the volcanic conduit must be due, either to the flow of magma from deep sources, accompanied by the gradual adjustment of the walls, or to the gradual expansion of magma due to change of pressure, or to changes of volume resulting from chemical readjustments whereby gaseous constituents are released from combination, or to an increase of temperature which must be due to chemical reactions within the magma.

One of the most remarkable facts about open craters of liquid lava is the maintenance of the temperature of the lava through long periods of time, with fluctuations that are periodic, though not strictly rhythmic, while in the case of intruded bodies the magmas cool and solidify in their conduits whatever their shapes. However, in these cases the time element is unknown, and is left out of the reckoning. Lavas exposed to the atmosphere in open craters should cool more rapidly than those surrounded by heated rocks, the more so because of the voluminous escape of gases whose expansion absorbs heat. The constant ebullition and continued liquidity of lavas in open craters indicate an equally continuous supply of heat. How is it supplied?

There is a striking analogy between the behavior of lavas in volcanic craters and that of hot springs and geysers, with certain fundamental differences. In some boiling springs the water remains at nearly constant levels in the basins, while outbursts of steam take place periodically from orifices in the bottom of the basins at

the end of conduits. In some springs there are rare periods of violent activity with eruptions of gases throwing water to great heights, as is the case with the Excelsior geyser in the Yellowstone Park, which during long intervals of time is merely a boiling spring. In other geysers, water rises within the conduit until the crater-like basin at its top is filled, when, after a period of gradually rising temperature, eruptions take place, and continue until much boiling water is discharged; after which the upper part of the conduit is emptied until the next period of ascension. This is the behavior of the Grand geyser. In still other geysers water does not reach the mouth of the conduit before eruptions take place from deep within, as in Old Faithful geyser. Neighboring geysers are independent of one another in their phases of activity, but all within one district may be specially active in one season or sluggish in another. There are individual peculiarities together with general resemblances.

The cause of geyser action is well understood so far as the explosive character is concerned. It depends on the accumulation of vapor pressure to increasing degrees at increasing depths within the conduit, due to the elevation of the boiling point of water with pressure, and to the greater temperature of the geyser's conduit at greater depths. So that the superheated water in the lower part of the column is kept from vaporizing because of the weight of the water above it, and gradually becomes hotter until convection currents heat the uppermost water in the conduit to the boiling point. If the loss of temperature at the surface equals the gain from below, no violent eruptions take place, the spring boils normally. If, however, the uppermost water becomes superheated to such an amount that violent ebullition takes place,

this act lifts enough water at the top to relieve the pressure on the more highly superheated water beneath, this bursts into vapor, pressure is lessened on water still farther below, and the process continues downward until the conduit empties itself more or less completely, hot water and steam blowing out like a volcanic eruption. The cause of eruption is the vapor pressure of the steam, or gas. The conduits of geysers are filled with water from the wall rocks, which finds its way through fissures from the earth's surface, and is more copious in times of abundant precipitation than in comparatively dry periods. The heat undoubtedly comes from deep-seated bodies of igneous rocks, not yet cooled.

In the eruption of lava from volcanic craters, the explosive agent is the gas within the lava, which is in fact the vapor of the lava, just as steam is the vapor of water. However, in the case of boiling springs water is the chief component of the lava, so to speak, which is vaporizable in large quantities at comparatively low temperatures, together with such other vaporizable substances as may be present, CO_2 or sulphur compounds; whereas molten rock lavas are chiefly silicate compounds which are very slightly vaporizable at the temperatures of volcanic lavas, so that the chief gases that escape are those that separate themselves from rock magmas at such temperatures under atmospheric pressure, that is, water gas, oxides of carbon and sulphur, free sulphur, and others.

From the behavior of lavas in craters it is evident that the vapor pressure of the magmatic gases varies from time to time, and that most of the characteristics of extrusion, aside from the eruption of great volumes of lava, are attributable to the action of gases. The boiling, and bursting of bubbles of gas, as at Kilauea,

the play of fountains of lava within crater pools, which occasionally occurs at Kilauea and at the summit of the Mauna Loa; the explosion of the tops of volcanic cones as at Vesuvius, or on the side of Etna; these are clearly the work of lava gases.

The gigantic explosions at Krakatau, however, were the result of the influx of sea water into an active crater, that had enlarged the openings of two small craters on a low volcanic island, which were in explosive action by reason of their own lava gases. When the enlarged crater lowered its edge to sea level the rush of water into the molten lava brought on more violent explosions that exposed more and more lava to the sea, until the reaction culminated in the gigantic explosions that deepened the crater 1,000 feet below sea level and exhausted the explosive energies of the volcano, permitting the chilling of the lava in the upper end of the conduit, which has since been quiescent. The violent explosion of Taal, in 1911, probably culminated when water from the lakes within the crater reached molten lava at the upper end of the conduit, and the same may have been the case with the eruption of Mont Pelée, in 1902. In like manner, the explosions that occur within the earth before the birth of a new volcano are occasioned, probably, by the access of molten magma to underground reservoirs of water, which may be porous beds of stratified rocks or open fissures containing water.

The eruption of lava without notable explosions may be due in part, in some instances, to the expansion of the magma through the liberation of gases from combination with other elements and the inflation of the magma; but it is probable that the volume of lava so erupted is very small compared with that which flows

out in consequence of dynamical movements within the lithosphere, as in fissure eruptions. In these eruptions, dynamical movements of a deep-seated character must be the dominant cause of flow. In eruptions from a volcanic cone, the expansive energy of gases may be the principal motive force, pumping out, as it were, little by little, magma from the top of a conduit, where equilibrium is slowly restored by the rise of magma from lower down, with the consequent necessity of volumetric adjustment of the enclosing lithosphere.

The Rôle of Gases

The function of gases in the activity of volcanic lavas is of the utmost importance in modifying their liquidity, internal movements and, to a considerable extent, their temperature. These effects have been noted in a previous chapter, but in a discussion of the causes of prolonged volcanic activity, with periods of violent action and long lapses of quiescence, it is necessary to inquire more closely into the possible supply of gases and their probable sources.

The gases that escape from lavas must have come from two general sources: one, the magma itself, that is, gases inherent in the composition of magmas in their primary basins; the other, surrounding materials of the lithosphere, the wall rocks. Assuming that the chemical elements constituting rock magmas, as they appear at the extremities of lava columns, were in existence during the aggregation of the materials composing the earth, according to an accretionary hypothesis, and that they were components of the substances originally brought together from space—they should exist in all parts of the earth, though in various amounts, according to the

manner of their accretion into a heterogeneous globe. Unless there are elements that have come into existence through processes and under conditions only possible after the earth had acquired a size in which it was capable of retaining an atmosphere of gases, it is not conceivable that elements may exist within the gaseous envelope that do not also occur within its solid mass. It is true that elements may become concentrated in certain zones of the earth where conditions favor their existence; as for instance, the concentration of nitrogen in the atmosphere, of silicon in the solid body of the earth, and probably the concentration of iron in the central portion. It is also true that extremely rare elements are concentrated in certain places, and are scarcely discoverable in others, as is the case with the rarer elements in mineral compounds which occur in some pegmatites; but it is not to be assumed that they do not exist in minute and variable amounts in all parts of the planet, unless it is supposed that they have been produced by some special or local generation from other forms of matter.

From this it follows that elements which appear as gases at the mouth of a volcanic conduit and were inherent in the magmas when in the zone of pseudo-rigidity, or of potential fluidity, should not differ in kinds from gaseous elements that exist in rock material immediately over that zone, or in higher, middle portions of the lithosphere. The same should be true for gaseous elements that may be derived from rocks in the upper zone of the lithosphere, except that the relative proportions of the various gaseous elements may differ from place to place, both in a vertical direction in the lithosphere and laterally throughout its extent. Unless some law of regular distribution of elements within the earth

should be established, the amount of different kinds of gaseous elements that may be acquired by molten magmas during their passage from their deepest source to the earth's surface must be considered to be a matter dependent on the chance heterogeneity of the lithosphere. There are, of course, well-known relationships between the composition of certain kinds of sedimentary rocks and certain kinds of elements that may appear in gaseous compounds at the surface of molten lavas; the carbonates in limestones and other rocks are capable of yielding abundant carbon dioxide; water contained in porous sediments and in hydrated minerals may furnish great volumes of water gas.

It is not to be expected, then, that there are any distinctions to be recognized between the kinds of gaseous elements inherent in rock magmas before they begin to move upward and those they may acquire by absorption from surrounding material during their ascent. However, there may be differences in the relative amounts of different gaseous elements inherent in rock magmas from particular primary basins, and of gases acquired from wall rocks at different places along their conduits; and it may be expected that the gases given off by various lavas in different parts of the world will not be alike in amounts, some being in extremely small, almost negligible, quantities.

It would seem reasonable to expect that whatever elements are present in a gaseous state in molten magmas for very long periods of time should be as uniformly disseminated through the magma as other chemical constituents which show themselves later on as mineral components. Certainly, if rock magmas are liquids at high temperatures, gaseous components, if present, should diffuse equably through them during

millions of years. If elements which appear as gases at the earth's surface were in combination with other elements in magmas under high pressures in deep zones, as previously suggested, they should be as uniformly distributed through the magma as the other elements with which they are combined; and if they are liberated from combination when pressure lessens, their dissemination through the magma should be quite as uniform as before.

On the other hand, gases that enter magmas from wall rocks should be most abundant in marginal parts of the body of magma, and since their diffusion through such viscous liquids requires considerable time, a rapidly flowing magma may reach the earth's surface before complete diffusion of recently acquired gases has taken place. The more viscous the magma, the less the diffusion, other things being equal. Rhyolitic lavas show much more evidence of incomplete gaseous diffusion than basaltic lavas. The flow of lava through irregularly shaped channels, the differential flow of parts having various viscosities, and possibly convection currents, while they tend to mix a magma and promote diffusion between parts having different concentrations, also produce streaks and bands of magma that are physically and chemically heterogeneous, which solidify into rocks with eutaxitic and banded structures.

The contact of molten magmas with limestones and other rocks bearing carbonates leads, in some instances, to the conversion of the carbonates to silicates and other compounds with the liberation of large volumes of carbon dioxide, which must escape, in part, into the liquid magma. The contact of molten magma with rocks containing water necessarily involves the conversion of water into gas at high pressure, and the absorption of

a large part of the gas by the magma. Nothing can prevent its entering the magma but impermeable wall rocks and a higher vapor pressure within the magma.

With the two general sources of gaseous elements to draw upon, how may periodic and irregular evolutions of gas at the upper extremity of volcanic conduits be accounted for? Are the gases supplied at irregular intervals at their sources? or are there irregularities in the process of transmission upward through the conduit? May both of these suggested causes of irregularity be operative?

The assumption that at great depths magmas are more viscous than near the earth's surface involves the idea of slower diffusion in them of gases at great depths than higher up in their conduits. If there are any chemical constituents in rock magmas at great depths capable of diffusing through the nearly rigid mass as though they were uncombined gases, their rate of migration should be much less than it is when the magmas become less viscous as they move upward. In a conduit filled with magma, which is more viscous downward, gases should diffuse more rapidly in the upper portions. They should pass upward more rapidly than they are supplied by basal portions of the magma column, so that in the course of time, if the magma remained stationary, less and less magmatic gases would reach the uppermost lava from the bottom of the conduit; consequently, there should be a dying out of energy from this source. There would seem to be no manner in which a new supply of magmatic gases could be obtained from the pseudo-rigid zone except by dynamic movements which would permit additional volumes of metastable magma to pass upward.

FIG. 83. SPINE OF MONT PELÉE, FROM THE NORTHEAST, MARCH 25, 1903

E. O. Hovey, Am. Mus. Nat. Hist.

However, there is the probability that compounds containing gaseous elements, which were stable under great pressures, may become unstable under less pressure, that is, when magmas exist at higher levels in the conduits, so that gases may be set free within the lava column at various altitudes, and thus add to the supply of magmatic gases which may diffuse upward, but such additional supply should be distributed gradually throughout the lava column, and most abundantly in the highest parts.

If there should be a check on the transmission of gases from deep-seated magmas, they might accumulate somewhere within the magma in the conduit until liberated and permitted to diffuse farther. Such a check might arise through stiffening, or increasing viscosity, of the magma in some part of the conduit. The most familiar operation of this kind is the cooling of lava in the mouth of a conduit, resulting in a very stiff, viscous mass, or in solidified rock. Gases accumulating beneath such a stopper, if they acquire sufficient vapor pressure before complete solidification of the topmost lava, may push it gradually up through the crater, as at Mont Pelée, in 1903, when a mass of stiffened lava was forced 800 feet above the crater walls, and formed the remarkable spine shown in Figures 83, 84, 85, which, in a short time, crumbled and fell to pieces.

If the topmost lava becomes too firmly solidified within the conduit, the accumulated gases must acquire energy enough to rupture the mass and explode their way through. If their strength is not sufficient for this, a rupture may occur in another part of the conduit, or surface activity may cease altogether. It is possible for magma to become highly viscous in particular places deep below the mouth of the conduit where the walls may

be nearer together than higher up, and where cooling might proceed faster than in broader parts of the channel. This should hinder the transmission of gases until they had accumulated in sufficient amounts to force the passage at this place. The irregularities of gaseous diffusion just considered might produce spasmodic, or periodic, volcanic activity, although the supply of gases from the deepest sources were uniform, or wholly magmatic in origin. They should operate similarly upon the diffusion of gases from wall rocks. However, there are other possible causes of irregularity in the supply of accessory gases from wall rocks that should be noted.

The absorption of accessory gases by molten lavas depends upon two conditions: the presence of vaporizable constituents, or of gases, in the wall rocks, and the relative intensities of the vapor pressures within the wall rocks and the magma in contact with them. If the vapor pressure is stronger in the heated wall rocks, gases will pass into the magma; if it is stronger in the magma, gases will escape into the wall rocks. At considerable depths, where water-charged rocks are under great pressures, the heating to magma temperatures should produce water gas at very high vapor pressure, and there should be a flow of gas into the magma, which may completely dissolve it. In the early stages of magmatic intrusion through water-soaked sedimentary rocks, or fractured rocks filled with water, there should be greater evolution of water gas than later on, when most of the available gas had passed into the lavas, and had been carried up to the earth's surface; so, early eruptions through a given conduit may be more gaseous and explosive than later ones.

Gases produced by chemical reactions between wall rocks and magmatic gases should be evolved more

Fig. 84. North side

Fig. 85. South side

Spine of Mont Pelée, March 8, 1903

A. Lacroix

slowly, and should enter magmas more gradually, than gas from superheated water. Magmas charged with sulphur and chlorine and their gaseous compounds when in contact with limestones should cause the decomposition of the carbonates with evolutions of carbon dioxide which should enter the magma. These processes of evolving gases should continue so long as the reactions and heating extended farther and farther into the surrounding rocks. If the stores of water, or of carbonates, were not distributed uniformly in the wall rocks the supply of gases from such sources should be variable. If new fractures permitted magma to have access to new stores of these constituents there should be fresh supplies of gases to be transmitted through the volcanic conduit. An increase in the supply might result from a movement of magma in the conduit, whereby hotter magma with unexpended sulphurous gases was brought into contact with carbonate wall rocks.

Near the earth's surface the vapor pressure in rocks surrounding volcanic conduits is more likely to be less than that within the column of lava, so that the magmatic gases should pass through the wall rocks away from the center of the volcano. Sulphurous and other strongly acid gases reacting on carbonated rocks should displace carbon dioxide and force it out in great volumes with other gases, producing solfatara, mofettes, and hot springs at some distance from volcanic craters.

The rôle of gases in maintaining the temperature of lavas by reason of chemical reaction within the magma has been referred to previously. This may be vital to the maintenance of volcanic activity in lava columns where little lava rises from deep-seated reservoirs, or does so only after great intervals of time. In such conduits the cessation of volcanic activity should follow

the failure of gases to arrive in sufficient quantities, either from deep-seated reservoirs because of insufficient diffusion, or local exhaustion; or from wall rocks because the supply was all absorbed; or because the supply was shut off by the metamorphism of the wall rock through crystallization into dense adinole, or other varieties of compact rock, through which water gas at high temperatures could only diffuse with extreme slowness, because of its viscosity and the minuteness of the capillary spaces in the rock. Since such rocks form where sandstones are traversed by molten magmas they reduce the supply of gas that should come from water-soaked sandstone strata.

Whatever may be the cause of periodic variation in the gas content of lavas in volcanic conduits, there are other variations in the amount of gases in magmas which appear to be regional, for throughout some great belts of country volcanic eruptions have been characterized by great explosiveness, forming mountain ranges and plateaux of tuff and breccias of wide extent, whereas in other regions numerous outflows of small bodies of lava have been nearly free from explosive products. Breccias form mountain ranges and plateaux in the Yellowstone Park region, in the San Juan region in Colorado (Fig. 86), in the Cordilleras of North and South America, and elsewhere. Small massive outflows of similar lavas with relatively few tuffs and breccias occur in many places in the Great Basin of Utah and Nevada, and in the Yukon valley in Alaska.

In the Yellowstone and San Juan regions the tuff-breccias are chiefly andesitic, and were earlier eruptions. Later eruptions of rhyolite and basalt were less explosive and form massive lavas. In these regions it appears that gases escaped in greater volumes with the

Fig. 86. Volcanic breccia, Dike Ridge, Cimarron Creek, Colo.

W. Cross, U. S. Geol. Surv.

earlier eruptions. In the Great Basin gases do not appear to have been so abundant in any of the magmas, the series of lavas being essentially the same in their range of composition in the regions compared, and representing similar degrees of differentiation. Was the apparent difference in gas content due to the condition or composition of the original magmas in the various regions? or did the rising lavas encounter different conditions of water content in the wall rocks in the several regions?

Composition of Lavas

The composition of the lavas of one volcano is not uniform or constant, although in some cases the lavas forming the outside of an active volcano may be much alike, and the material of a very small cone may be nearly homogeneous in composition. However, when studied closely variations are discovered, and the larger the volcano, the longer its period of activity, and the greater the exposure of its older lavas, the greater the range of variation in the composition of its lavas, as a general rule. This is well illustrated in the dissected volcanoes of the Yellowstone Park region, and is shown to a less extent in the volcanoes of the Pacific Coast, especially Mount Shasta and Lassen Peak, in California, and also in Vesuvius and Etna.

Great variation is commonly shown in lavas of neighboring volcanoes, as in the group comprising Etna, Stromboli, Vulcano, and others in the Æolian Islands; or in the volcanoes of the Hawaiian Islands, or those about San Francisco Mountain in Arizona; and in many others. The lavas of a single volcano usually exhibit a general sequence of varieties, successive outflows

during long periods having somewhat diverse compositions, which in dissected volcanoes may be very pronounced between the first and last flows. The lavas that have been erupted almost contemporaneously from different volcanoes in the Æolian Islands differ from one another considerably; the lavas of Etna are basaltic, those of Vulcano dacitic; rhyolitic obsidian has been erupted in several localities in Lipari and Vulcano, besides andesitic and leucite-bearing lavas in other places. In general, the oldest eruptions were basaltic and andesitic, followed by more siliceous andesites, dacites, and rhyolites, contemporaneous with which were basalts and leucite-basanites.

In the denuded volcanoes at Electric Peak in the Yellowstone Park, at Crandall Basin, Wyoming, and at Haystack Mountain, Montana, the most abundant rocks in the stocks, or solidified conduits, are diorites and gabbros grading into more siliceous, granite-like rocks, which were the last eruptions within the solidifying stocks, filling fractures and contemporaneous veins in the earlier dioritic and gabbroic masses. These later lavas were in smaller volumes, which may not have reached the outside of the volcanoes. In the marginal parts of the Crandall volcano there are dikes of complementary rocks having different compositions from one another and from those of the other lavas of the volcano. In like manner, lavas having exceptional compositions were erupted in the marginal parts of the Crazy Mountain district, Montana, the rocks of the central stock having compositions and relationships very similar to those in the stocks of the volcanoes farther south. In other regions it has been noted that basaltic lavas occur in dikes in marginal parts of a volcano, while granitic rocks occur at its core.

Complementary rocks, some rich in ferromagnesian minerals, others rich in feldspathic ones, occur in parallel dikes in the Absaroka Range in the Yellowstone Park region. Other complementary rocks, rhyolites and basalts in much greater volumes as lava flows, form the plateaux of the Yellowstone and the lava plains of Idaho. Similar lavas occur as separate bodies and as mixed and blended bodies in great variety on the Isle of Skye, according to Harker.[7] In this region, quartz-porphyry and basalt occur together forming the same sills and mixed dikes; while granite and gabbro are intermingled to variable extents in some of the larger intrusive bodies.

In order to explain the variations and relationships just mentioned, it has been assumed that magmas possessing intermediate compositions, which are somewhat different in different regions, are erupted from deep-seated sources, and that in some instances, oftenest in the early stages of eruptive activity, they reach the earth's surface, or somewhere near it, without much, if any, modification of their original compositions. Subsequently, these primary magmas undergo differentiation in composition to various degrees, which appear as varieties of magma that are erupted in later periods of volcanic activity; the latest eruptions in a particular series usually being the most diverse. Since different varieties of lava in a series are erupted from one conduit or volcano in some places, and from neighboring volcanoes or orifices in others; and since a series of varieties may be erupted in small volumes from single volcanoes in an early stage of prolonged activity, and similar varieties of lava may be erupted in much larger

[7] Harker, A., and Clough, C. T. Geol. Survey, Great Britain, Memoir, The Tertiary Igneous Rocks of Skye, 1904, 197.

volumes from other vents in the district, in much later stages of the same period of activity, it follows that the differentiation of the magmas must proceed contemporaneously at different rates in different parts of the system of conduits which furnish the lavas of the region.

Since the most potent factors promoting magmatic differentiation are probably differences of temperature and chemical constituents, chiefly gases, which maintain molecular mobility within cooling magmas, differentiation should advance more rapidly in those parts of conduits where there are greater differences of temperature between wall rocks and magma, and where there may be greater percentages of gaseous components. Since other chemical constituents affect the molecular mobility of molten magmas in various degrees, notably the various silicate compounds themselves, the extent and the products of differentiation should vary with the chemical composition of the particular magma undergoing modification. In cooler parts of a conduit near the earth's surface, magmas should differentiate more rapidly than in deeper places, where temperature changes within a magma must be much slower and much less, it being understood that in either case the molecular mobility of the magma must be sufficient to permit differentiation. Since the process must be a gradual one, the variously modified portions of a body of differentiating magma must exist in juxtaposition within the conduit, or subsidiary reservoir; and since eruptions may happen while changes in composition of the magma are taking place, the lavas that flow out must represent various phases of the process, and may vary in composition from one part to another for the reasons just given.

Solidification of Rock Magmas

As molten magmas cool they solidify, usually with crystallization. When rapidly chilled they may be more or less glassy according to the rate of cooling and the chemical composition of the magma. The more viscous magmas oftenest form glasses. The more gradual the cooling the larger the crystals, and the more mobile the magma at crystallizing temperatures the larger the crystals. It is not known to what extent pressure affects the size of crystals, but in so far as it prevents the escape of gases from magmas it affects crystallization appreciably. Magmas that are chilled or cooled rapidly on the earth's surface are fine-grained, or more or less glassy; so also those that are chilled or rapidly cooled by intrusion into cool wall rocks are fine-grained or glassy, and are in some instances indistinguishable from extruded lavas. Magmas intruded into heated wall rocks cool more slowly, as do also the central portions of large hot magmas; they become coarse-grained rocks. Large bodies of magma intruded for long distances through cool wall rocks cool rapidly and crystallize into fine-grained rocks.

The forward end of a body of magma that is being intruded into cool rocks encounters cooler wall rocks than the rear of the same stream encounters, for the walls have been heated by the forward part of the intruding magma. The margin of a body of magma, or the parts in contact with wall rocks, may be cooled more rapidly than central portions and may form fine-grained rocks. So it happens that the grain of rocks, the size of their component crystals, depends primarily on the experiences of their magmas during eruption, largely with regard to their rates of cooling. However,

it is to be remembered that the composition of molten magma, especially the content of gaseous constituents, is a very considerable factor in its crystallization into rocks.

Fine-grained rocks may occur intruded thousands of feet below the earth's surface, and coarse-grained ones may have solidified between hot walls, or in very large masses, within a few hundreds of feet of the surface of the earth. Examples of the former are fine-grained porphyries forming sills and laccoliths at the base of the Paleozoic series under 11,000 feet of strata in the Gallatin Mountains, in the Yellowstone National Park, and many other sills and dikes of porphyry at similar depths in other regions. Examples of coarse-grained rocks that solidified at higher horizons are the diorites and granites in the volcanic stock at Electric Peak, in Cretaceous strata, 8,000 feet higher up than the first-mentioned porphyries in the Gallatin Mountains; also the gabbro and diorite in the core of the Crandall volcano, Wyoming, which is in volcanic breccia above the former surface of the earth at this place. The granite of Hörtekollen, in Norway, according to W. C. Brögger, solidified within less than 1,000 feet of the earth's surface.[8] In many other localities, coarse-grained rocks intersect bodies of porphyry, or have solidified at higher horizons.

It is not the depth at which magmas solidify that controls their coarseness of crystallization; the very largest crystals occur in pegmatitic veins or dikes, and in portions of large bodies of medium-grained rock where molecular mobility, due to concentration of gaseous constituents, permitted more complete diffusion and the growth of gigantic crystals. Pressure affects

[8] Brögger, W. C. Zeitschr. Kryst. Min., 16, 1890, 73.

the behavior of gaseous constituents, the chemical equilibrium of the compounds into which they enter, and their liberation from combination and from solution; but the possibilities of combinations within rock magmas are so many, the transitions often so sluggish, and the variations in pressures so gradual, that no distinctions can be discovered between rocks solidified under different pressures or at different depths; consequently, distinctions that were formerly supposed to characterize rocks as "plutonic" and "volcanic" have been found to be inappropriate, and without actual significance.

Summary

The problem of volcanism is concerned chiefly with the eruption of igneous magmas through the solid rocks of the outer zone of the earth, and with the various attendant phenomena. Its consideration involves a discussion of the fundamental characteristics of the earth, its physical condition, and its behavior toward the forces, or stresses, operating within it, especially in the exterior zone of rocks.

From astronomical and geological considerations it appears that the earth is to be thought of as a solid body having nearly twice the rigidity of steel; the outer zone, possibly somewhat over thirty miles thick, having a rigidity like that of plate glass. The density of the central portion must be considerably greater than that of the outer rocky zone, the lithosphere, and may consist mostly of iron with smaller amounts of other constituents that occur in rocks. The density of the lithosphere varies regionally, and is lighter beneath continents than under oceans. The variation in regional density appears to be of the same order of magnitude as the difference

in the densities of the average igneous magmas in various regions, so far as these can be determined. To this extent, the lithosphere appears to be heterogeneous laterally, and it may be inferred that lateral heterogeneity exists to some extent within the deeper parts of the globe.

The temperature of the interior of the earth is unknown. Only the most superficial parts have been studied in scattered localities, with discordant results. Temperature increases with depth, but not in constant or uniform ratios. Consequently, the rates of increase beyond the depths investigated, and the possible maximum temperature within the earth, are matters of a wholly speculative nature, which are not limited by astronomical theories respecting nebulæ or a possible nebular origin of the solar system. The temperatures actually observed in volcanic lavas do not exceed 1300° C. Rock minerals have melting points below 2000°, more nearly 1000° C. in many cases; and they form molten solutions which are liquid at temperatures below the melting points of the constituent minerals, and become more liquid when they contain gaseous constituents.

In order to maintain the rigidity of the globe, it seems to be necessary to assume, either that its temperature is not high enough to convert the materials into liquids, or that the effect of high temperature is offset by that of pressure. But the effects of moderately high pressures on the viscosity of rock substances are probably much less than the effects of high temperatures, so that very high temperatures seem to be precluded from consideration. It is possible that the balance between the effects of temperature and pressure is such that there may be a zone beneath the frangible portion of the lithosphere which may behave toward sudden stresses

as though it were rigid, but may act under prolonged strain like a highly viscous liquid. This pseudo-rigid zone may be the source of igneous rock magma, which may shift its position in consequence of warping of the lithosphere; and when a proper system of stresses permits, may flow between parting walls, and rise into higher horizons.

Warping and fracture of the lithosphere, probably consequent upon a shrinking inner globe, appear to be the prerequisites for magmatic extravasation; the magma following planes of fracture, wherever the stresses in the wall rocks and the magmatic pressure permit its intrusion. Where the stresses in the wall rocks press them together with a force greater than the magmatic pressure, no intrusion takes place. In cases where magmatic pressure exceeds the pressure of the containing walls, magma may spread them apart, or in those places where the stresses acting within the wall rocks tend to force, or bend, them apart, magma may intrude itself, and may form bodies of various sizes, the largest of which have been called batholiths, because the position of the underlying wall rock has not been located, and the imagination pictures the intruded body as very deep.

Melting and solution of wall rocks by molten magmas take place to some extent in some instances, but in amounts quite subordinate to the volume of the intruded magma in any case. However, in very many instances there is no appreciable solution of wall rocks by magmas.

It is probable that lavas which pour out in large volumes during fissure eruptions, especially the latter portions of such eruptions, reach the earth's surface at nearly the temperature they possessed within the reservoirs from which they flowed. Such eruptions may be but slightly affected by the expansive or explosive

properties of gaseous constituents, although these may assert themselves in surface portions of the lava flows, wherever the pressure is not sufficient to keep them in solution.

Gaseous constituents are probably more active and effective where surrounding pressure is slight, that is, near the surface of the earth; where they may escape from combination with other elements in the magma, may diffuse more readily through it, may increase its liquidity, and by making new chemical combinations may maintain, or even augment, its temperature, and when their vapor pressure is great enough they may inflate the lava to pumice, or explode it to dust, and shatter surrounding rocks to breccia.

These appear to be some of the principal factors in the problem of volcanism as it presents itself at this time. In discussing them, a number of possibilities have been suggested regarding the physical and chemical status of the interior of the earth, and some that seem to be probabilities. But it must be remembered that the actual behavior of mineral matter at high temperatures and under very great pressure has yet to be determined, and it may be that the limitations of laboratory investigation may leave the major part of the problem regarding the interior of the earth beyond the reach of definite knowledge, a perpetual subject for imaginative speculation.

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ORO-BATHYGRAPHICAL CHART OF THE WORLD

SHOWING AREAS OF VOLCANIC ACTIVITY, WITH THE OCEAN "DEEPS" ACCORDING TO SIR JOHN MURRAY

MARY DEEP
SUPAN DEEP
TUSCARORA DEEP
MURRAY DEEP
LOVER DEEP
AGASSIZ DEEP
TANNER DEEP
BACHE DEEP
BARLEY DEEP
WYMAN DEEP
Tropic of Cancer
SIGSBEE DEEP
THOULET DEEP
SUIKO DEEP
LIBBEY DEEP
KELTIE DEEP
MILL DEEP
NARES DEEP
PEAKE DEEP
MONACO DEEP
CHUN DEEP
HJORT DEEP
MAKAROFF DEEP
MOSELEY DEEP
BARTLETT DEEP
SWIRE DEEP
POURTALES DEEP
AGASSIZ DEEP
BROOKE DEEP
AMMEN DEEP
MOSER DEEP
GRAY DEEP
DANA DEEP
CAMPBELL DEEP
GARRETT DEEP
HILGARD DEEP
WEBER DEEP
MACLEAR DEEP
PLANET DEEP
WHARTON DEEP
Equator
MILNE EDWARDS DEEP
KRUMMEL DEEP
BARTHOLOMEW DEEP
RICHARDS DEEP
HAECKEL DEEP
Tropic of Capricorn
KRECH DEEP
ZHD DEEP
BUCHANAN DEEP
HAVERGAL DEEP
GARDINER DEEP
ENTERPRISE DEEP
THOMSON DEEP
LORIEN DEEP
JEFFREYS DEEP
ROSS DEEP
VALDIVIA DEEP
Arctic Circle
Antarctic Circle

CONTOURS SHOWING HEIGHT OF LAND

12000 Feet	3658 Metres
6000	1829
3000	915
600	183
SEA LEVEL	

CONTOURS SHOWING DEPTH

SEA LEVEL	
100 Fathoms	183 Metres
500	915
1000	1829
1500	2744
2000	3658
3000	5487
4000	7317
Below 4000	

AREAS OF VOLCANIC ACTIVITY.

Areas in red are districts of modern and late Tertiary volcanic activity.

All depressions below 3,000 fathoms (5,487 metres) are termed Deeps and are here coloured dark blue.

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